Bureau d'Enquêtes et d'Analyses
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SAFETY STUDY

Oxygen fire in cockpit study - Accident to the A320 registered SU_GCC on 19 May 2016

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PREAMBLE

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SPECIAL FOREWORD TO ENGLISH EDITION

This is a courtesy translation by the BEA of the study.

As accurate as the translation may be, the original text in French is the work of reference.

Contents

Glossary

Abbreviation	Definition
A/P	Auto-Pilot
EAAID	Aircraft Accident Investigation Directorate / Egyptian Ministry of Civil Aviation
ACARS	Air Communication Addressing and Reporting System
AIROPS	EU regulation No 965/2012
AMU	Audio Management Unit
APU	Auxiliary Power Unit
ATC	Air Traffic Control
CAM	Cockpit Area Microphone
CFR	Current Flight Report
COPIL	Co-pilot
CRC	Continuous Repetitive Chime
CVR	Cockpit Voice Recorder
EASA	European Aviation Safety Agency
ECAM	Electronic Centralized Aircraft Monitor
EICAS	Engine Indicating and Crew Alerting System
ELT	Emergency Locator Transmitter
FAA	Federal Aviation Authority
FAR	Federal Aviation Regulation
FCOM	Flight Crew Operating Manual
FDR	Flight Data Recorder
FLxxx	Flight Level
PA	Public Address
PBE	Protective Breathing Equipment
PF	Pilot Flying
PM	Pilot Monitoring
QRH	Quick Reference Handbook
UTC	Coordinated Universal Time

SYNOPSIS

Oxygen fire in cockpit study
Accident to the A320 registered SU-GCC

SAFETY INVESTIGATION

Opening of investigation

Following the accident on 19 May 2016 over the Mediterranean Sea, involving an Airbus A320 registered SU-GCC operated by EgyptAir, a safety investigation was opened. In compliance with the international texts in force, and in particular Annex 13 to the Convention on International Civil Aviation, as the accident occurred in international waters, Egypt's Aircraft Accident Investigation Directorate (EAAID), as the State of Registry and State of the Operator of the aeroplane, was charged with the safety investigation.

The BEA appointed an Accredited Representative for France as the State of Design of the aeroplane, assisted by technical advisers from the aircraft manufacturer, Airbus and from the European Aviation Safety Agency (EASA). The American safety investigation authority (NTSB) also appointed an Accredited Representative for the United States as State of Manufacture of the engines.

Organization of investigation

Sea searches located the wreckage and the flight recorders were recovered. In July 2016, the data from the Cockpit Voice Recorder (CVR) and the Flight Data Recorder (FDR) was extracted under the authority of the Egyptian Investigator In Charge, in the BEA laboratory in France.

The EAAID publicly communicated the following information: a fire had broken out on board the aeroplane and was identified by the crew; the flight recorders had stopped while the aeroplane was still in cruise at an altitude of 37,000 ft.

In the scope of the investigation, the BEA shared with the EAAID, information about previous occurrences where there had been fires in the presence of an oxygen leak in the cockpits. In these occurrences, there was a leaking noise comparable to that present on the CVR recording of this occurrence.

In December 2016, the EAAID announced the discovery of traces of explosives on victims and stated that, in accordance with Egyptian legislation, the case was transferred to the Egyptian Attorney General who would from now on be responsible for carrying out the investigation.

The BEA was not able to confirm this finding. Furthermore, no other factual information available to the BEA supported the hypothesis that an explosion had occurred on board the aeroplane.

OXYGEN FIRE STUDY

Initiation of study

The BEA proposed to the EAAID, to continue the work into the accident, using the occurrences identified above. As it was not possible for the EAAID to continue the safety investigation, the BEA carried out a study on oxygenated fires in the cockpit, convinced that a more detailed analysis of the accident to flight MS804 could provide safety lessons to be shared with the international aviation community.

Scope

In the event of depressurisation or smoke, the members of the crew and the passengers may need to use oxygen. For this eventuality, pilots have quick-donning masks at their disposal, stowed in storage boxes on both sides of the cockpit.

	
Fixed breathing equipment (quick-donning)	*Location of fixed breathing equipment in commercial air transport aeroplanes*

The study carried out by the BEA focused on the following subjects:

- the possible mechanisms leading to a fire and a pressurised oxygen leak in or near the oxygen mask storage box;
- the spread of a fire in the presence of a pressurised oxygen leak;
- the possibilities for extinguishing this type of fire;
- the acoustic characterisation of these phenomena.

The fire breakout mechanisms studied included external sources of heat (lithium batteries in electronic devices or glowing cigarettes), internal ignition in the hoses or the ignition of grease and dust in the oxygen-enriched environment.

Fire fed by pressurised oxygen - Test results

Details of the tests and results obtained are summarised in several videos (Video 1 and 2 /4) and confirm that a sound runaway comparable to that produced by a blowtorch is present when the mask assembly catches file when the system is supplied with pressurised oxygen. In this case, the flames are large and the fire spreads rapidly to the surroundings of the storage box.

The results on how the fire spreads in the environment of the oxygen distribution system are also the subject of a video (Video 4/4).

Lastly, a video (Video 3/4) shows the ineffectiveness of using a halon fire extinguisher, present inside the cockpit of flight MS804, on a fire fuelled by a pressurised oxygen leak.

Application of study results to accident to flight MS804

The accident sequence began while the aeroplane was cruising at 37 000 ft (11 277m), with a cabin crew member present in the cockpit, the captain resting in his seat and the co-pilot flying.

The first event of the accident sequence which could be identified was a flow of oxygen for 2.6 s via the co-pilot's mask regulator. This flow had the same characteristics as when the *EMERGENCY* knob of the mask is pressed when the box has not been reset. The investigation was not able to determine if this flow was linked to a human action.

The storage box of the co-pilot's mask was thus highly enriched in oxygen as a result of this flow. A loud transient noise of unknown source occurred at this point in the mask storage box. It has not been possible to determine what generated this loud noise. Less than half a second later, the noise of a continuous oxygen flow appeared again. A fire started in the co-pilot's mask storage box, and was fuelled by the pressurised oxygen leak. It has not been possible to determine which came first: the fire or the oxygen leak. Neither has it been possible to determine the cause of the fire.

Whichever the case, the oxygen-fed fire spread to the outside of the storage box. This type of fire is rapid, large-scale and difficult to control. It produces a characteristic noise comparable to that of a blowtorch. The study has shown that the protection and extinguishing equipment available on board aeroplanes is not sufficient to control this type of fire.

The fire very probably then damaged the computer power supply systems, which led to the disconnection of the autopilot in particular. No crew actions were recorded in the cockpit. It has not been possible to determine whether the crew remained or not in the cockpit, whether they were unconscious in the cockpit or whether they had fled the fire and then returned or remained outside the cockpit. The aeroplane entered an uncontrolled flight path and collided with the sea.

SAFETY RECOMMENDATIONS

In addition to research into the accident scenario, the study has highlighted the safety issues associated with the oxygen systems present on board heavy commercial air transport aeroplanes.

The presence of the oxygen distribution system has a twofold impact:

- the air may become enriched with oxygen in the vicinity of the supply system due to micro-leaks, mask tests or a rupture of a part in the oxygen supply system. The presence of oxygen makes the elements more inflammable and the start of a fire more likely;
- a fire that damages the oxygen systems, if it causes a hose to rupture, becomes an oxygen-enriched fire that is difficult to control.

Certification requires that the occurrence of an uncontrolled oxygen fire is extremely unlikely. Several in-flight and on-ground occurrences gave rise to thought being given not only to the means of preventing these fires, but to their propagation and the means of fighting them.

Further work taking into consideration the effects of overpressure in the oxygen system

The tests carried out by the BEA in the scope of this study were based on the assumption that the pressure in the system was 5 bar. Internal ignition mechanisms such as particle impact, grease oxidation or ignition by electrostatic discharge may depend on the oxygen pressure. Similarly, the fragility created by a nearby external source of ignition could be greater in the event of a high-pressure leak.

EASA, in collaboration with the manufacturers, carry out additional risk analyses to take into account the hypothesis of an overpressure in the distribution system and its consequences in terms of failure mechanisms. The results should be analyzed with regard to the potential factors explaining the scenario of flight MS804. These analyses may require additional testing as part of a research program.

Propagation of a fire fed by an oxygen leak

The events and the tests carried out have highlighted the size of the fire and the speed at which it spreads in the case of a fire fuelled by an oxygen leak. These fires produce a characteristic sound, comparable to that of a blowtorch, and significant heat (recognisable by the whiteness of the flame).

Two on-ground occurrences and the tests showed that halon fire extinguishers are not suitable for treating fires fuelled by an oxygen leak.

In the events on the ground, the crews were unable to control the fires and evacuated the cockpit. In flight, fighting an oxygen-enriched fire requires the oxygen supply to be immediately cut off.

Consequently, the BEA recommends that EASA assess the appropriateness of cockpit fire/smoke procedures incorporating the recognition of an oxygen fire (identifiable by a characteristic noise comparable to that of a blowtorch) and the immediate cutting off of the oxygen supply in this case, and if necessary review the requirements for installing and carrying protective equipment *independent of the oxygen distribution system.*

Risks linked to the use of cigarettes in the cockpit

International regulations are not explicit about banning smoking in the cockpit of commercial air transport aeroplanes. While there are warnings about smoking near oxygen in the passenger compartment, there are no similar warnings with respect to the cockpit. The decision seems to rest with the captain.

No systematic and obvious danger has been established from smoking near an oxygen mask storage box, even with a mask in the EMERGENCY position or when the box has not been reset. However, if a cigarette is introduced into the storage box - unlikely but possible - a fire may start, accompanied by an oxygen leak. In this case, the flames would be large and the fire would spread rapidly to the surroundings of the storage box.

Consequently, the BEA recommends that EASA ensure that the danger represented by a glowing cigarette in the cockpit be taken into account, the associated risks assessed and that certification and operational regulations be amended where applicable.

1. CONTEXT

Following the accident to an Airbus A320 registered SU-GCC and operated by EgyptAir, on 19 May 2016 over the Mediterranean Sea, a safety investigation was opened. In compliance with the international texts in force, as the accident occurred in international waters, the Egyptian safety investigation authority (EAAID), as the State of Registry and State of the Operator of the aeroplane, was in charge of carrying out this investigation.

The BEA appointed an accredited representative, France being the State of Design of the aeroplane, and was assisted by technical advisers from the aircraft manufacturer, Airbus and from EASA. The American safety investigation authority (NTSB) also appointed an accredited representative, the United States being the State of Manufacture of the engine.

Sea searches located the wreckage and the two flight recorders were recovered. The initial work on the flight recorders was carried out under the authority of the Egyptian Investigator In Charge (IIC), in the BEA laboratory. At the beginning of July 2016, the data from the Cockpit Voice Recorder (CVR) and the Flight Data Recorder (FDR) was extracted, read and decoded.

During this work, the EAAID published the following elements about the accident:

- the flight recorders stopped operating while the aircraft was in cruise at an altitude of 37,000 ft;
- the aircraft systems sent ACARS messages indicating the presence of smoke in the toilets and the avionics bay;
- the data from the FDR confirms these messages;
- the playback of the CVR reveals, in particular, that the flight crew mentioned the existence of a fire on board;
- several pieces of debris were retrieved from the accident site. Some of these showed signs of having been subject to high temperatures, and traces of soot.

In December 2016, the EAAID announced the discovery of traces of explosives on human remains and stated that, in accordance with Egyptian legislation, the case was going to be transferred to the Egyptian Attorney General who would from now on be responsible for carrying out the investigation.

The BEA proposed carrying out additional work on the debris and recorded data to the EAAID, to better understand the sequence of events.

In fact, based on the initial observations of the debris and the first analyses of the recorder data, the BEA considered that the most likely hypothesis was that a fire broke out in the cockpit while the aeroplane was flying at its cruise altitude and that the fire spread rapidly resulting in the loss of control of the aeroplane.

The BEA searched for previous occurrences where there had been a fire in the cockpit, particularly focusing on those where it was reported that there had been a loud hissing sound[1] as was the case in the CVR recording of flight MS804.

Three events which occurred on the ground where the CVR recording was available were identified. From a psycho-acoustic view point, the loud hissing that can be heard on the CVR of flight MS804 has

[1] Noise similar to that produced by a pressurised gas leak.

similarities with those recorded during these events. All three correspond to leaks in the oxygen systems in the cockpits (see paragraph 3).

With these events in mind, the BEA was convinced that there were most probably safety lessons to be learned and shared with the international aviation community based on a more detailed safety analysis of the SU-GCC accident. The BEA thus proposed continuing the work to their Egyptian counterpart. As it was not possible for the EAAID to resume the safety investigation, the BEA continued the safety analysis of the event and carried out a study on oxygenated fires in the cockpit.

This work led the BEA to conclude that there were indeed safety lessons to be shared with the international community and safety issues that would lead to safety recommendations. The BEA has drawn up this document to describe the work carried out, the conclusions that can be drawn from it and the resulting recommendations.

The BEA sent this document, in draft form, to the EAAID and the NTSB, inviting them to confirm that they had no objection to its publication.

The EAAID made known its objection to the public release of any information or data relating to flight MS804. EAAID has undertaken to resume the safety investigation and to prepare a draft final accident report in the coming six months.

The BEA, pursuant to standard 6.8 of Annex 13[2] relating to the option given to States participating in the investigation to issue safety recommendations after coordination with the State conducting the investigation, has taken the decision to issue safety recommendations and provide the document supporting these recommendations.

This document has been sent to EASA on a confidential basis. EASA is allowed to share this document, on a confidential basis, solely with the persons who need to be involved in the processing of the safety recommendations.

The BEA, pursuant to standard 6.8 of Annex 13[3] relating to the option given to States participating in the investigation to issue safety recommendations after coordination with the State conducting the investigation, has taken the decision to issue the safety recommendations and the document supporting them.

This document is composed of the following parts.

The first section (paragraph 2) describes the regulatory requirements concerning the oxygen system in the cockpit and the firefighting means.

The second section (paragraph 3) describes four events which occurred on the ground in which there was a fire and oxygen leak.

The third section (paragraph 4) is devoted to describing and understanding the SU-GCC accident sequence.

The fourth section (paragraph 5) describes the examinations carried out to understand:

[2] Annex 13 to the Convention on International Civil Aviation

[3] Annex 13 to the Convention on International Civil Aviation

- certain fire break-out (ignition) mechanisms likely to affect the cockpit's oxygen system;
- the spread of a fire fed by an oxygen leak;
- the means to extinguish an oxygen-rich fire available in the cockpit.

The fifth section (paragraph 6) sets out partial conclusions with respect to the accident to SU-GCC and enlarges on the resulting safety issues.

Finally, the sixth section (paragraph 7) presents the safety recommendations addressed to EASA and the manufacturers. These recommendations concern the continuation of the work, the procedures for fighting oxygenated fires and the regulations concerning smoking in the cockpit.

2. OXYGEN SYSTEM AND FIREFIGHTING IN THE COCKPIT

In the event of depressurisation or smoke, the members of the crew and the passengers may need to use oxygen.

The large commercial air transport turbo jets are in the majority of cases, equipped with three separate oxygen systems:

- oxygen directly available in the cockpit for the crew's use;
- oxygen available in the cabin, above each seat, for the passengers and cabin crew;
- portable oxygen equipment for the crew or passengers used in the event of an emergency or when giving first aid.

This chapter is dedicated to the oxygen system in the cockpit to be used by the crew.

2.1 Supplemental oxygen - regulatory requirements

For pressurised aeroplanes operated at pressure altitudes above 25,000 ft, regulatory requirement CAT.IDE.235 of consolidated European regulation (EU) No 965/2012, known as "AIROPS" indicates that the quantity of supplemental oxygen must cover, for all crew members, the flight time with a cabin altitude above 13,000 ft and a flight time of -30 minutes for a cabin altitude between 10,000 and 13,000 ft and in no case less than two flight hours.

Quick-donning type masks must be available for pilots. This type of mask:

(a) can be placed over the face from the pilot's seat, properly secured, sealed and supplying oxygen on demand, with one hand in less than five seconds, and then remain in position with both hands free;

(b) can be donned without interfering with the wearing of glasses and without delaying the pilot in the performance of assigned emergency tasks;

(c) when fitted, does not prevent immediate communication between flight crew members and other crew members via the aircraft's intercom system; and

(d) does not prevent radio communication.

For aircraft weighing more than 5,670 kg, the dedicated supplemental oxygen equipment must meet the certification specifications described mainly in paragraphs CS25.869 and CS25.1441 (or FAR equivalent).

CS25.869 indicates that the system must be installed in such a way that escaping oxygen cannot cause ignition of grease, fluid or vapour accumulations that are present in normal usage conditions or as a result of failure or malfunction of any system.

CS25.1441 adds that the oxygen system must be free from hazards in itself, in its method of operation, and in its effect upon other components.

The means of compliance AMC 25.1441 details the risk analyses that can be carried out to meet these requirements.

With regard to the installation of the oxygen system, in addition to the requirements described in CS25.869, the AMC for CS 25.1441(b) indicates that potential external sources of ignition must be studied and the associated risks minimised.

The compartments in which oxygen systems are installed must provide adequate protection against possible contamination; these compartments must be adequately ventilated and the routing of the system must be insulated.

In addition, the oxygen hazard analysis must show that the oxygen systems and their components are designed in such a way that the occurrence of an uncontrolled oxygen fire in the aircraft is extremely unlikely and does not result from a single failure. This analysis must assess the combustion and ignition mechanisms, and in particular the following aspects:

- equipment failure (excluding failures due to human error during assembly);
- operating conditions;
- components and materials, with particular reference to spontaneous-combustion temperatures in a 100% oxygen-enriched atmosphere;
- ignition mechanisms;
    - the analysis must cover the possible internal ignition mechanisms, taking into consideration as a minimum: particle impact[4], rapid pressurization[5], flow friction[6], resonance[7], mechanical impact[8], galling and friction[9], fresh metal exposure[10], static discharge[11], electric arc[12], chemical reaction[13] and thermal runaway[14],
- kindling chain;
    - the analysis must look into the ability of a fire to propagate and burn through a component. If one of the ignition mechanisms exists, the kindling chain must be analysed.

The following design elements must also be considered: high-pressure shut-off valve, pressure-limiting device, isolation, material of hoses, grounding, joints and recharging systems.

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[4] Heat generated when small particles strike a material with sufficient velocity to ignite the material and/or the particle.

[5] Heat generated during the rapid compression of a gas (usually less than one second) from a low pressure to a high pressure.

[6] Heat generated by the flow of oxygen along a polymer and the appearance of erosion, friction and/or vibration.

[7] Heat generated by acoustic oscillations within resonant cavities which cause a rapid rise in temperature.

[8] Heat generated by one or more impacts on a material with sufficient energy to ignite it.

[9] Heat generated by two parts rubbing against each other.

[10] Heat generated by the oxidation of a non-oxidised metal in an oxidising atmosphere.

[11] Heat generated by the discharge of accumulated electrostatic charges, with sufficient energy to ignite the material.

[12] Heat generated by an electric current sufficient to create an arc from a source of electricity and capable of igniting materials.

[13] Heat generated by the combination of chemical compounds capable of igniting surrounding materials.

[14] Heat generated by the accumulation of liquid or solid materials that can undergo self-sustaining exothermic reactions.

To sum up, the oxygen system must be installed in such a way that:

1. The impacts of an external source of ignition are minimised.

2. The immediate environment is preserved, i.e. an oxygen leak cannot cause the ignition of substances close by.

3. And the system's design is such that a single failure of one of its components does not lead to an uncontrolled fire in the aeroplane and that in all cases, such a fire is extremely improbable.

To meet these requirements, the risk analysis of the oxygen system must look at the failures of the various components, the most unfavourable uses, the properties of the materials and the internal ignition mechanisms. If an internal ignition mechanism exists, the associated fire kindling chain must be analysed.

In the remainder of this document, the term ignition will be used. The term external ignition mechanism will be used when talking about elements located outside the oxygen system, i.e. elements that were originally outside the mask stowage boxes, for example the runaway of a lithium battery of a device in a nearby document storage compartment.

The term internal ignition mechanism will be used when talking about sources inside the oxygen system, for example the heat released when a metal particle collides with a wall.

2.2 Description of cockpit oxygen system on a commercial air transport aeroplane

On the majority of large commercial air transport jets, there is a supply of oxygen stored in one or more bottles (capacity of 1,400 to 3,200 l), pressurised to more than 100 bar, under the cockpit floor. A distribution system allows pressurised oxygen (around 5 bar) to flow from the cylinder, via a regulator, to the masks located on each side of the cockpit. These masks are positioned for use, if required, by the two pilots and two people which may be on the jump seats in the cockpit.

On some aeroplanes, the crew can control the arrival of the oxygen in the system via a control panel located in the cockpit to open or close a solenoid valve. The crew have information screens indicating the oxygen pressure in the cylinder.

The masks are stowed in metal boxes by the side of the seats and can be easily accessed by the crew. It must be possible to remove the mask from the box with one hand and in a single movement, inflate the harness, place the mask on the face and tighten the harness.

The masks are composed of a visor and a regulator to supply oxygen at a pressure close to the ambient pressure each time the pilot breathes in. An *EMERGENCY* knob on the mask regulator can be used to produce a continuous overpressure of a few millibars in the oronasal cavity and a continuous flow of a few litres of oxygen in the ocular cavity and thus prevent the ingress of contamination (smoke).

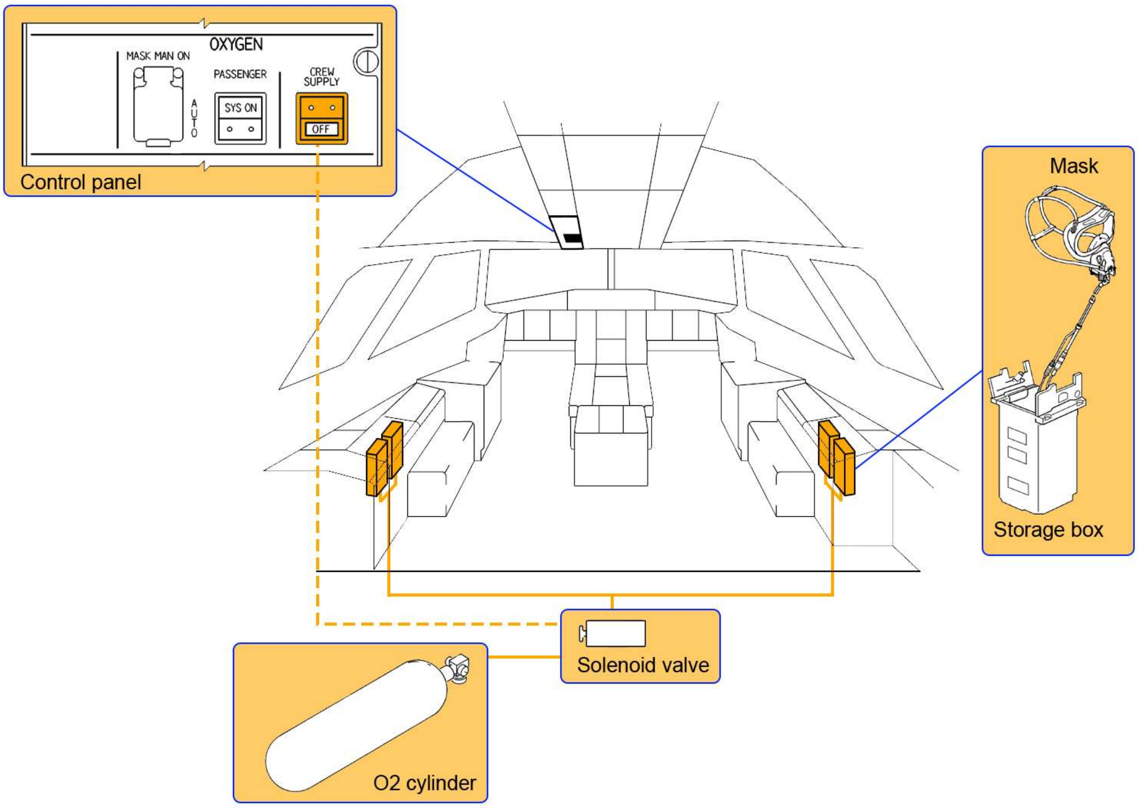


Figure 1: description of cockpit oxygen system of a commercial air transport aeroplane

Some aeroplanes are equipped with flow fuses in the oxygen system, located close to each mask storage box. These flow fuses close and cut off or limit the oxygen flow to the associated mask when a leak is detected downline.

2.3 Firefighting means

2.3.1 Fire extinguishing equipment

The fire protection and fire-fighting systems on most large commercial air transport aeroplanes include:

- fire and overheating detection and extinguishing systems for the engines and APU;
- smoke detection and extinguishing systems for baggage compartments and lavatories;
- smoke detection for the avionics bay(s);
- portable fire extinguishers for the cockpit and passenger cabin.

Regulation CAT.IDE.A.250 indicates that the type and quantity of extinguishing agent for the required fire extinguishers shall be suitable for the type of fire likely to occur in the cockpitand AMC.CAT.IDE.A.250 specifies that at least one fire extinguisher must be present in the cockpit, and that it must be suitable for fighting liquid fires and electrical equipment fires.

Historically, halon 1211[15][16] was the most common agent used in portable fire extinguishers on aircraft. Minimum Performance Standards (MPS) for extinguishing agents are defined in Appendix A of DOT/FAA/AR-01/37 dated August 2002, while acceptable criteria for selecting extinguishers containing these agents are defined in FAA Advisory Circular AC 20-42C.

Halon is due to disappear from cockpits in the near future (by the end of 2025), as the use of this gas will soon be banned for environmental reasons.

Three alternatives to halon are currently known and comply with the MPS:

- HFC-227ea;
- HFC-236fa;
- HFC Blend B.

2.3.2 Protective breathing equipment

The AIROPS European regulatory requirement CAT.IDE.A.245 specifies that all pressurised aeroplanes must be equipped with Protective Breathing Equipment (PBE) to protect the eyes, nose and mouth and to provide for a period of at least 15 minutes, oxygen for each flight crew member.

AMC1 CAT.IDE.A.245 specifies that this function can be provided by quick-donning masks.

Figure 2: fixed breathing equipment (quick-donning)

In part CAT of the AIROPS, it is also indicated that aeroplanes must be equipped with an additional portable PBE installed adjacent to the hand fire extinguisher. Some operators have not adopted the installation of a portable PBE next to the hand fire extinguisher. In particular, certain companies have recently modified their configuration by installing a fire extinguisher behind the captain and a hood behind the co-pilot.

[15] CF2ClBr - Bromochlorodifluoromethane

[16] AMC 25.851 (c)

Figure 3: portable breathing equipment

Airbus A320 Boeing 777

Figure 4: examples of a PBE installation on a commercial air transport aeroplane (source: BEA)

2.3.3 Smoking in a cockpit

Smoking has been banned on domestic and international flights in most countries since the 1990s. China is cited as being the last country to authorise pilots to smoke in the cockpit (up to 2019).

For commercial air transport aircraft, the European certification specification CS25.853 indicates: "*Smoking is not allowed in lavatories. If smoking is allowed in any area occupied by the crew or passengers, an adequate number of self-contained, removable ashtrays must be provided in designated smoking sections for all seated occupants*."

In Europe, the AIROPS regulatory requirement CAT.OP.MPA.240 specifies that the captain shall not allow smoking on board:

"*(a) whenever considered necessary in the interest of safety;*
(b) during refuelling and defuelling of the aircraft;
(c) while the aircraft is on the surface unless the operator has determined procedures to mitigate the risks during ground operations;
(d) outside designated smoking areas, in the aisle(s) and lavatory(ies);
(e) in cargo compartments and/or other areas where cargo is carried that is not stored in flame resistant containers or covered by flame-resistant canvas; and
(f) in those areas of the passenger compartment where oxygen is being supplied."

Manufacturers still provide ashtrays. In the toilets, this corresponds to a type certification requirement. In the cockpit, the installation of ashtrays is an option that can be requested by the customer company.

Figure 5: example of an ashtray in an Airbus A330 cockpit (source: BEA)

Figure 6: example of an ashtray in a Boeing 777 cockpit (source: BEA)

3. ACCIDENTS PRIOR TO THE ACCIDENT TO SU-GCC, INVOLVING A FIRE AND THE OXYGEN SYSTEM IN THE COCKPIT

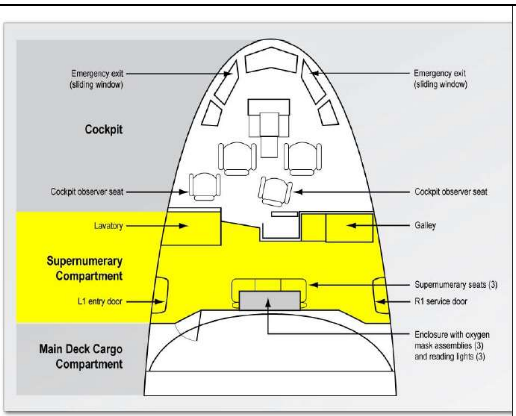
The following events were selected on the basis of the following criteria:

- an oxygen leak and a fire were identified and the intensity of the fire was aggravated by the oxygen leak;
- for all of them, the authorities in charge of the investigation indicated a hissing sound corresponding to a leak under pressure;
- for three of them, sound recordings were available;
- the sounds recorded during the events show very close similarities with the recording of the flight MS804.

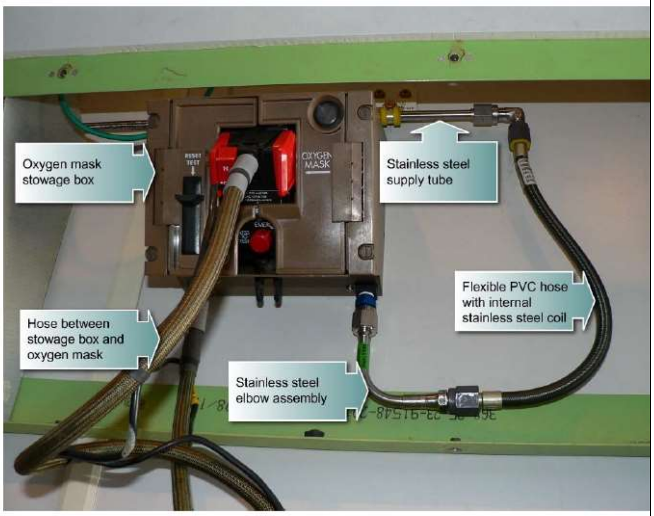
The events described below occurred on the ground. No particularity linked to this specificity has been identified. In other words, the accident scenarios are transposable to flight and can be compared with the accident of flight MS804 which occurred in flight.

3.1 Accident to the Boeing 767 cargo registered N799AX in 2008

The accident occurred on 28 June 2008 on the ground at San Francisco. The NTSB investigation report contains recommendations on the design of the oxygen hoses.



a. location of compartment



b. oxygen distribution system

c. oxygen supply hose

d. damage following fire

Figure 7: images from investigation report (source: NTSB)

The fire broke out during flight preparation, in the compartment between the cockpit and the cargo area (see Figure 7a).

The captain and co-pilot evacuated the aeroplane through the cockpit windows after closing the cockpit door and calling in the aircraft rescue and firefighting service. The aeroplane was considered destroyed due to the extent of the damage (see Figure 7d).

The compartment where the fire occurred contained three oxygen masks supplied by an oxygen cylinder independent of the cockpit oxygen supply.

The investigation showed that a short-circuit energised the spring in the oxygen hoses, which became a source of ignition; the hose caught fire and the oxygen promoted combustion. The fire spread to adjacent materials.

The pilots reported that, while performing the engine start-up checklist, they heard loud “pop” and “hissing” sounds. This was confirmed by the spectral analysis of the CVR recording that shows that the event begins with a transient noise (pop), immediately followed by a loud hiss. The hissing sound was recorded for about 1minute, until the CVR was switched off. The popping and hissing sounds were consistent with the ignition of an oxygen hose by an internal rather than external heat source.

From a psycho-acoustic point of view, this recording shows similarities with the CVR of the MS804.

Lessons learnt - Intermediate conclusion
The mechanism involved in the accident to N799AX was an internal ignition in the system (linked to the design of the hoses) which caused a rupture in the oxygen hose and consequently a fire fuelled by an oxygen leak which led to the destruction of the aeroplane. The crew evacuated the aeroplane without trying to put out the fire.

3.2 Accident to the CRJ 200 registered N830AS in 2009

The accident occurred on the ground at Tallahassee on 28 February 2009.

The NTSB investigation report indicated that the fire broke out in the cockpit. A flight attendant and the captain of the aeroplane perceived an unusual hissing sound quickly followed by smoke and signs of a fire. They evacuated the aeroplane.

The investigation determined that the fire initiated in the top portion of a junction box which contained components associated with the distribution of electrical power from the APU or an external AC power supply.

The fire ignited combustible materials and spread upwards toward an oxygen hose mounted above the junction box. The oxygen mask of the third crew member was installed in the top forward portion of the wardrobe unit.

The oxygen hose ignited when exposed to the fire, and the fire burned through the aeroplane's fuselage.

After the event, it was observed that the pressure indicator of the oxygen cylinder supplying the cockpit indicated 0 psi (showing that it had emptied during the event) and that the oxygen mask hoses of the third crew member had been damaged.

Hissing is audible on the CVR for around ten seconds, after which the CVR was switched off.

Lessons learnt - Intermediate conclusion.

The mechanism involved in the accident to N830AS was damage to the oxygen system by a fire which had broken out nearby. The fire caused a rupture in the oxygen hose, resulting in a fire fuelled by an oxygen leak. The crew evacuated the aeroplane without trying to put out the fire.

3.3 Accident to the Boeing 777- 200 registered SU-GBP in 2011

The accident occurred on the ground at Cairo on 29 July 2011. The EAAID investigation report indicates that fire and smoke appeared on the right side of the co-pilot following a pop and hissing sound.

The captain asked the co-pilot to exit the cockpit and to warn the crew of the fire. The captain used the cockpit fire extinguisher, situated behind his seat, to fight the fire. This attempt was unsuccessful, and the fire continued to spread in the cockpit.

	
Damage inside the cockpit	Exterior damage

Figure 8: photos from investigation report (source: EAAID)

The evidence gathered during the investigation did not make it possible to determine whether the oxygen system ruptured first, creating a flammable environment, or whether the oxygen system ruptured as a result of the aeroplane fire.

The report indicated that the accident could be linked to the following probable causes.
1. An electrical fault or short circuit resulted in electrical heating of flexible hoses in the flight crew oxygen system (electrical short circuits; contact between aircraft wiring and oxygen system components may be possible if multiple wire clamps are missing or fractured or if wires are incorrectly installed).
2. Exposure to electrical current.

Lessons learnt - Intermediate conclusion.

The mechanism involved in the accident to SU-GBP has not been determined: it is possible that the oxygen system was damaged by a fire that broke out nearby, or that a hose ruptured, creating a flammable environment. The crew used a halon fire extinguisher, which did not put out the fire.

3.4 Accident to a Boeing 737 in 2012

The accident occurred on the ground during the push-back. The authority in charge of the safety investigation who has not yet published a rapport gave the following information to the BEA.

An oxygen leak and fire broke out in the cockpit on the captain's side. It is said that two seconds after the start of the leak, the co-pilot reported the problem and called out "cologne". The captain asked the pilots to leave the cockpit and asked for a fire extinguisher. A fire extinguisher was activated one minute later. The passengers were evacuated and the aircraft rescue and firefighting service intervened to being the fire under control. The fire caused substantial damage in the cockpit as well as in the electronic and avionics bays along with heat damage to the outer skin.

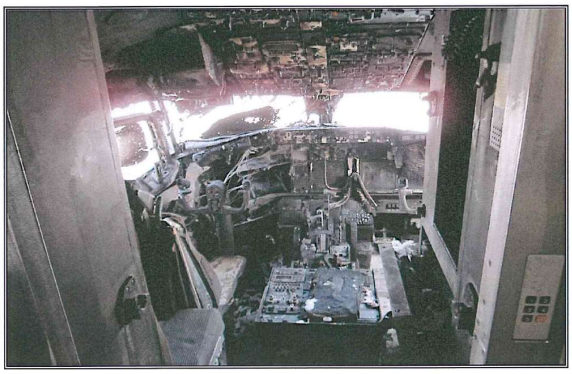


Image of General Cockpit Damage

Figure 9: photo from draft investigation report (source: safety investigation authority)

It is believed that the crew reported seeing a ball of sparks heading towards the captain's oxygen mask and that the mask and its surroundings burst into flames accompanied by the noise of escaping oxygen. The fire was out of control and the flames very high within approximately five seconds. Thick black smoke escaped from the cockpit.

The captain tried to stop the leak by squeezing the hose of the mask and to put out the fire using a halon fire extinguisher. He then indicated that this fire was not a fire to be put out with these fire extinguishers.

The investigation authority reported the following findings:

- after the event, the captain's oxygen mask was found on the floor, on the right side of the flight control lever;
- the mask had been left in the *EMERGENCY* position;
- the captain lit up a cigarette 2 min 21 s before the start of the leak.

Questions remain about the scenario of the event.

It is thought that the event began with an initial continuous leak of pure oxygen, this oxygen leak then spreading into the cockpit. The fire started as a result of a perfume and a burning cigarette meeting. The fire then spread inside the cockpit after the captain opened the mask storage box in order to fight the fire.

According to the information provided by the investigation authority, the CVR recorded an initial hissing sound lasting 3.5 s. The hissing sound stopped for less than two seconds. A new hissing sound was perceptible for less than one second which then increased in volume. The total duration is thought to be 5 min 17 s. A slow decrease in the strength of the hissing could be heard until the CVR stopped. This could be explained by the progressive damage to the cockpit microphone.

Lessons learnt - Intermediate conclusion.

The mechanism involved in the accident has not been determined with certainty: it is thought that there was an initial leak which, on contact with an external heat source, caused a fire which was then fuelled by a flow of oxygen from a mask in the *EMERGENCY* position, which had been removed from its box. The crew were said to have emphasised the speed and extent of the fire. It is thought that the crew used a halon fire extinguisher, which did not put out the fire before the evacuation of the aeroplane.

3.5 Conclusion with respect to prior events involving a fire and the oxygen system in the cockpit

These events, and in particular the content of the sound recordings when available, were used to characterize the noise caused by an oxygen-fed fire.

These events cannot be considered as precursors for the start of the MS804 accident sequence. The equipment was different and the causes of the fire may differ. For those events where the design of the hoses was considered a contributory factor, the faults identified have been corrected.

However, these events have the following features in common:

- the fire was rapid and large-scale;
- damage was extensive;
- all the crews had to evacuate the aircraft;
- the sounds recorded during the events show very strong similarities with the recording of the flight MS804.

In two of these events, the crews attempted to extinguish the fire, but were unable to do so.

4. ACCIDENT TO THE AIRBUS A320 REGISTERED SU-GCC OPERATED BY EGYPTAIR ON 19 MAY 2016

The following information is based on the information which came to the knowledge of the BEA.

4.1 History of the flight

On 18 May 2016, the crew aboard the A320, registered SU-GCC, took off at 21:21[17] from Paris - Charles-de-Gaulle airport (France) bound for Cairo (Egypt). The co-pilot was the PF[18] and the captain was the PM[19].

The aeroplane reached its cruising altitude of 37,000 ft shortly after 21:43. At 23:48, the crew exchanged for the last time with the Greek air traffic control.

At around 00:30, the aeroplane disappeared from the Greek secondary surveillance radar.

The data from the primary radar showed that the aircraft successively turned left and then right in descent.

A signal from the aeroplane's Emergency Locator Transmitter (ELT) was transmitted at 00:36:59.

4.2 Injuries to persons

	Injuries		
	Fatal	Serious	Minor/None
Crew	10		
Passengers	56		
Others			

All the crew members and passengers were fatally injured.

Note: The ten crew members included three security agents.

4.3 Aircraft information

4.3.1 Airframe

Aeroplane type	Airbus A320
MSN	2088
Registration	SU-GCC
Date of delivery	3 November 2003

[17] Except where otherwise indicated, the times in this report are in Coordinated Universal Time (UTC).
[18] Pilot Flying.
[19] Pilot Monitoring.

Cycles	Approx. 20,687 cycles
Flight Hours	Approx. 47,866 hours
Engines	IAE V2500-A5

4.3.2 Maintenance

On 16 May 2016, a maintenance operation carried out on the aeroplane at Cairo led to the replacement of the storage box for the co-pilot's oxygen mask.

After this maintenance action, the aircraft performed 10 flight cycles, for a total time of 32 flight hours and total elapsed time of 72 hours.

4.3.3 Oxygen supply system in cockpit

4.3.3.1 Description of system

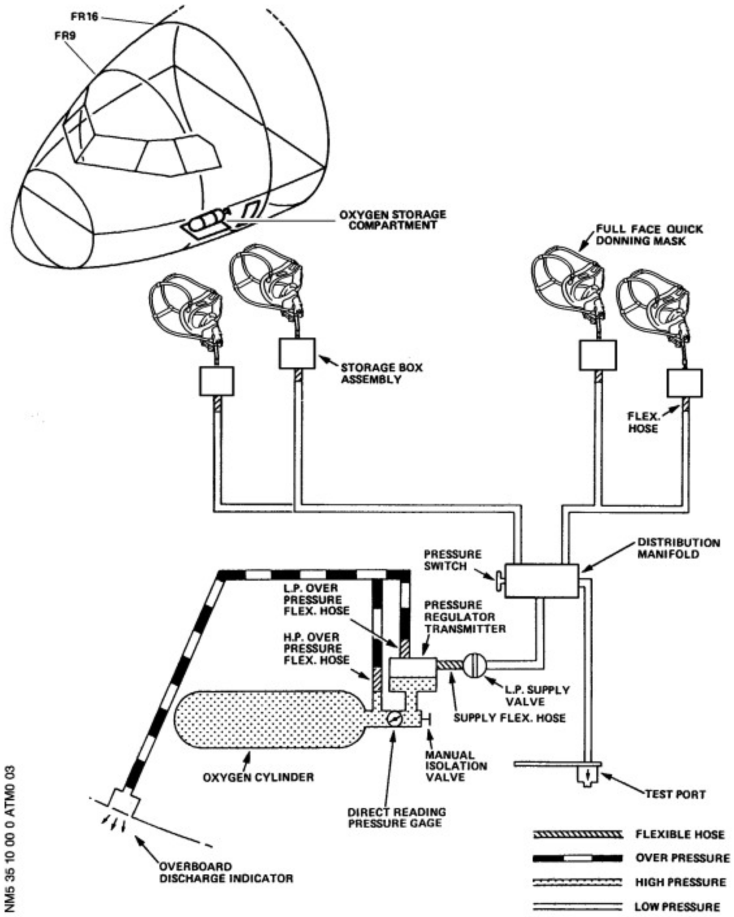


Figure 10: diagram of Airbus A320 oxygen system layout (source: Airbus AMM)

Oxygen is stored in an oxygen cylinder under the cockpit.

A regulator located on the head of the cylinder reduces the pressure to 5 bar in the downstream system.

In the event of overpressure, a valve evacuates oxygen to the outside of the aircraft.

A solenoid valve, called DVE on the Airbus A320, or LP SUPPLY valve on the diagram above, controlled from the cockpit by a *CREW SUPPLY* pushbutton located on the overhead panel, cuts off or authorises the flow of oxygen (at a pressure of 5 bar) to the masks.

The oxygen then travels from the regulator, under the cockpit floor through rigid stainless steel lines to four mask storage boxes located on the left and right side of the cockpit (two on each side). The boxes are connected to the rigid line by flexible hoses (soft hoses protected by a metal braid tube). This connection is in the cockpit's side compartments where the boxes are housed.

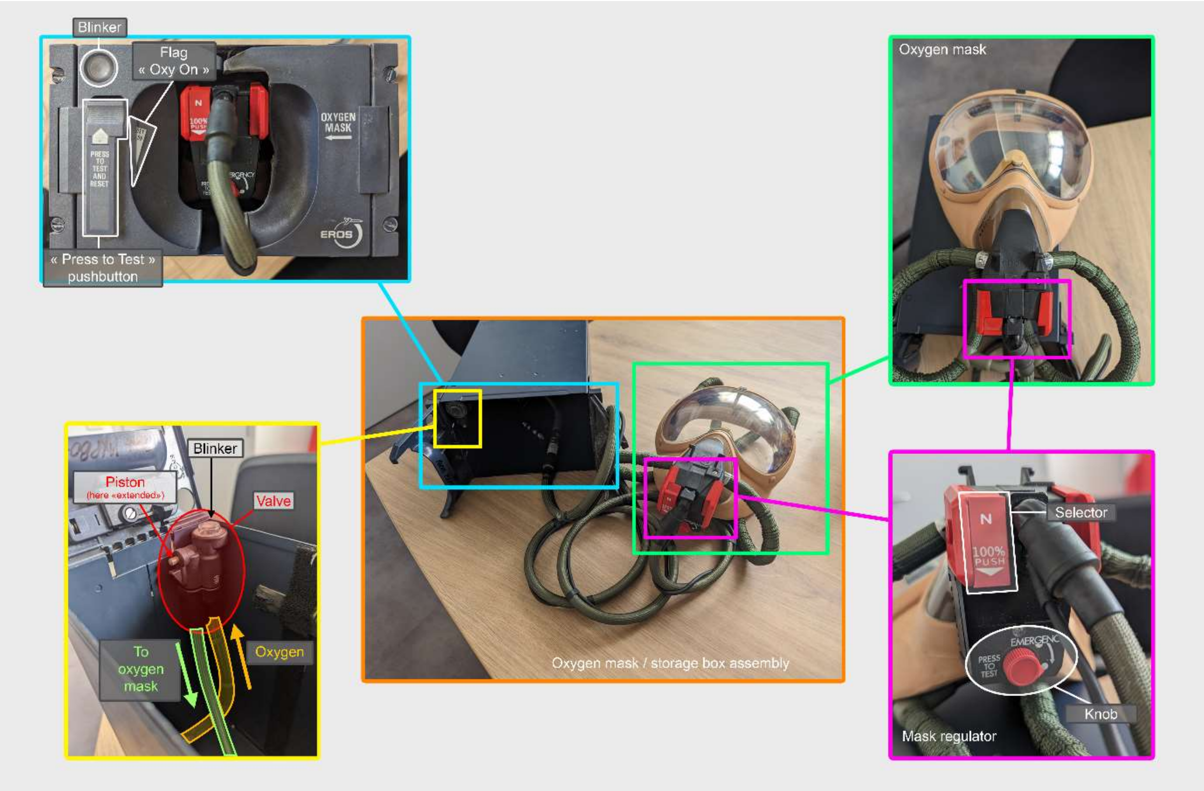


Figure 11: storage box and oxygen mask

In the mask storage box, a first hose (Dekabon - aluminium tubing in a nylon sheath) connects the box inlet to a valve. Inside the valve, a piston is mechanically held in the closed position. It prevents the flow of pressurised oxygen (5 bar) to the mask.

When the *PRESS TO TEST* pushbutton is pressed or the box door is opened, the mechanical stop is moved. The piston slides and oxygen flows through the lines to the mask. In the same way, this piston presses a microswitch which activates the mask microphone.

When the piston is not in its closed position and the left-hand box door is folded down, the piston comes to a stop on a plastic element and an *OXY ON* flag is moved, indicating that the mask is supplied with oxygen.

Similarly, the flow of oxygen through this valve activates a 'pop-out' (*blinker*) membrane to confirm the flow of gas when the pilot breathes.

A green hose connects the valve to a quick-release union with a check valve, enabling the mask to be disconnected and replaced without oxygen leaking.

Another hose (grey) connects the union to the mask regulator. These hoses are made up of silicone tubes surrounded by a braided tube made of Nomex (a type of Kevlar), which has no elastic properties and prevents the hose from swelling.

The regulator sends oxygen (or a mixture of air and oxygen, depending on the position of the selector) to the pilot each time he breathes in, at a pressure close to the atmospheric pressure. A system of chambers, diaphragms and pressure differentials regulates this pressure.

On the regulator, a selector can be used to choose the 'N' position, which sends a mixture of air and oxygen[20] adapted to the cabin's pressure altitude, or the "100%" position, which sends only pure oxygen (used in the case of cabin smoke, for example).

In addition, a knob can be used to select the *NORMAL* or *EMERGENCY* position. In the *NORMAL* position, the flow of oxygen is triggered by the person wearing the mask breathing in. With each breath in, the mask delivers a mixture of air and oxygen ("N" position) or pure oxygen ("100%" position). In the *EMERGENCY* position, the mask delivers oxygen with a continuous overpressure.

Some of the oxygen is used in the mask to defog the visor and keep a positive pressure under the mask to prevent the ingress of smoke.

The EMERGENCY knob can be both turned and pressed. Pressing the *EMERGENCY* knob performs the *PUSH-TO-TEST* function and triggers a flow of oxygen into the mask (flow equivalent to the *EMERGENCY* position) for as long as the knob is pressed and there are no obstacles preventing the overpressure from building up.

The cockpit oxygen system on SU-GCC was equipped with a high-pressure oxygen cylinder with a capacity of 3,256 l (115 cubic feet) (NTPD[21]) at a pressure of 127.5 bar (1,850 psig).

4.3.3.2 Associated procedures

The FCOM specifies the minimum quantity to be carried.

[20] The air in the mixture is taken from the ambient air in the cockpit.
[21] Normal Temperature Pressure Dry.

Ident.: LIM-35-00001943.0004001 / 16 NOV 11
Applicable to: ALL

MINIMUM FLIGHT CREW OXYGEN PRESSURE

REF TEMPERATURE (1)		Deg.C	-10	0	10	20	30	40	50
		Deg.F	14	32	50	68	86	104	122
MIN (2) BOTTLE PRESSURE (PSI)	2 CREWMEMBERS		468	486	504	522	540	558	576
	2 CREWMEMBERS	+1 OBS	606	629	652	675	698	721	744
	2 CREWMEMBERS	+2 OBS	759	788	817	846	875	904	933

(1) *REF TEMPERATURE :*
- *On ground : REF TEMPERATURE = (OAT + COCKPIT TEMP) / 2*
- *In flight : REF TEMPERATURE (deg. C) = CAB TEMP (deg. C) -10 °C*
  or
  REF TEMPERATURE (deg. F) = CAB TEMP(deg.F)-18 °F

(2) *MINIMUM BOTTLE PRESSURE TO TAKE INTO ACCOUNT :*
- *Preflight checks*
- *The use of oxygen, when only one flight crewmember is in the cockpit*
- *Unusable quantity (to ensure that the regulator functions with minimum pressure)*
- *Normal system leakage*
- *and*
  Protection after loss of cabin pressure, with mask regulator on NORMAL (diluted oxygen):
  - *During an emergency descent : For all cockpit members for 13 min*
  - *During cruise at FL 100 : For 2 flight crewmembers for 107 min.*

  or
  Protection in case of smoke, with 100 % oxygen : For all cockpit members for 15 min at a cabin altitude of 8 000 ft.

Note: The above times are based on the use of a sealed mask, but may be shorter if the flight crewmember has a beard.

Figure 12: minimum oxygen to be carried for flight (source: Egyptair A320 FCOM)

Check of quantity of oxygen available

The crew check the quantity of oxygen available before the flight. During the flight, if the cylinder pressure drops to below 400 psi, the corresponding page (DOOR/OXY) is displayed on the ECAM.

Oxygen system operating procedures

When preparing the cockpit, the crew check that there is no pushbutton with a white light illuminated on the overhead panel and set the cockpit oxygen to ON if this has not been done beforehand.

Each oxygen mask is then checked.

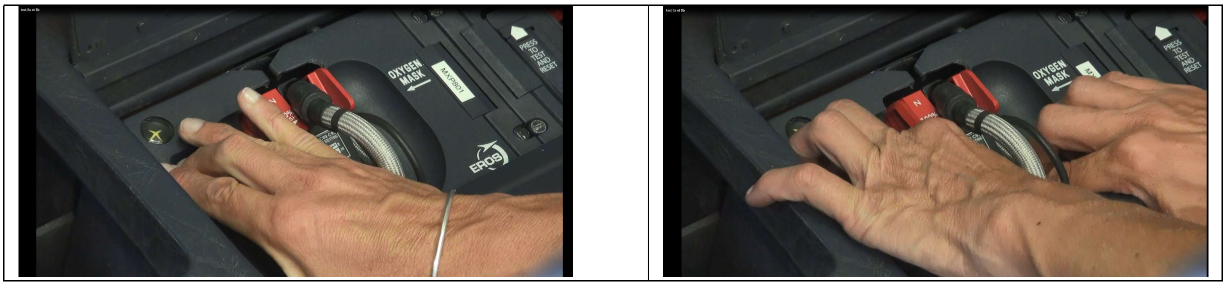
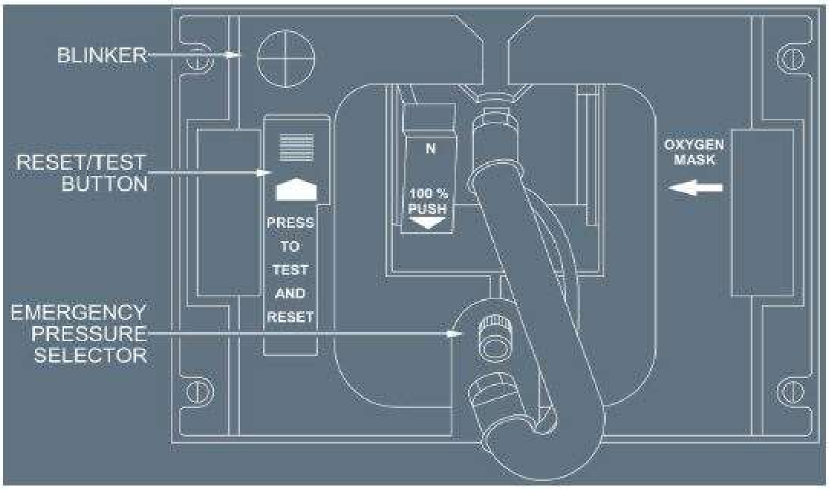


Figure 13: view of actions of oxygen mask test procedure (source: BEA)

The oxygen mask test procedure described in the FCOM is the following:

Ident.: PRO-NOR-SOP-06-00011249.0002001 / 23 JUN 15
Applicable to: ALL

OXYGEN MASK TEST



WARNING	To prevent hearing damage to ground mechanics connected to the intercom system, inform them that a loud noise may be heard in the headset when performing this test.

On the OXYGEN panel:

CREW SUPPLY pb.. CHECK ON

On the glareshield:

LOUDSPEAKERS..ON

On the audio control panel:

INT reception knob.. PRESS OUT-ADJUST
INT/RAD sw..INT

On the mask stowage box:

- Press and hold the reset/test button in the direction of the arrow.
  - Check that the blinker turns yellow for a short time, and then goes black.
- Hold the reset/test button down, and press the emergency pressure selector.
  - Check that the blinker turns yellow and remains yellow, as long as the emergency pressure selector is pressed.
  - Listen for oxygen flow through the loudspeakers. Warn any engineer, whose headset may be connected to the nose intercom, that a loud noise may be heard when performing this check.
- Check that the reset/test button returns to the up position and the N 100 % selector is in the 100 % position.
- Press the emergency pressure selector again, and check that the blinker does not turn yellow. This ensures that the mask is not supplied.

On the ECAM DOOR/OXY page:

REGUL LO PR message..CHECK OFF

The crew must perform this check after having checked all masks. It ensures that the LP valve is open, (due to residual pressure between the LP valve and the oxygen masks, an LP valve failed in the closed position may not be detected during the oxygen mask test).

Figure 14: oxygen mask test procedure PRO-NOR-SOP-06 P14 and P15/16 (source: Egyptair A320 FCOM)

The oxygen mask test procedure is designed to check:

- That the oxygen mask storage box is supplied with oxygen; when the test pushbutton is pressed, oxygen is admitted into the hose up to the mask and the pressure is balanced at 5 bar in the box hoses upstream of the oxygen mask regulator. The visual indicator (called a *blinker* in the procedure) opens and a yellow dot appears when the pressure is balanced, then closes and turns black when the pressure is the same everywhere.

  While the test pushbutton is being pressed, the piston that allows oxygen to flow to the pilot's mask moves and, via an electrical contactor, activates the link between the microphone and the audio system. During this basic test, there is no continuous noise of an oxygen flow.

- That the box is supplied with oxygen and that the mask and microphone are functional.

  By simultaneously pressing the *PUSH TO TEST* pushbutton on the box and the *EMERGENCY* knob on the mask, a continuous flow of oxygen is established from the oxygen supply to the nose cup via the regulator. Oxygen is then released into the box. The microphone picks up the noise produced by this flow of oxygen and the sound can be heard on the cockpit loudspeaker.

- That the box is effectively in the reset position (i.e. the piston that allows oxygen to flow to the mask is in the closed position, preventing oxygen from being delivered to the mask). Just pressing the mask's *EMERGENCY* knob does not release any oxygen and the blinker fed by the flow downstream of the piston does not change colour (from black to yellow).

4.3.4 Fire-smoke in cockpit procedures

4.3.4.1 Smoke/Fumes/Avionics smoke procedure

The philosophy of the procedure described in the FCOM is as follows: in the event of fire/smoke, a diversion must be considered as soon as smoke is detected. The aim is then to identify the source of the smoke/fire and to combat it. If the source is not identified, is not visible or not accessible, and cannot be extinguished, the diversion must be started immediately. If the smoke is detected by the crew and there is no procedure displayed on the ECAM, the crew must refer to the QRH.

The immediate actions are to:

- protect the crew, in particular by the wearing of oxygen masks;
- prevent further contamination (spread);
- communicate with the cabin crew.

At all times, the elimination of smoke, the compliance with the ELEC EMER procedure and the immediate landing must be considered.

4.3.4.2 Specific procedure for lithium battery fires

For lithium battery fires, the actions are specified in the FCOM as follows: the PF dons his oxygen mask while the PM dons the PBE/hood and if there is a flame, uses the halon extinguisher.

It is indicated that halon extinguishers are effective on flames but cannot stop a thermal runaway. It is also indicated that if necessary, the control of the aeroplane should be transferred to the pilot on the opposite side of the fire.

4.3.4.3 Protective breathing equipment

A hood is located on the right-hand side of the cockpit, at the rear.
Another hood is located on the left-hand side of the cockpit.

The FCOM states that this system protects a crew member's eyes and respiratory system when fighting a fire, in the event of smoke, harmful gas emissions or depressurisation.

4.4 Wreckage and debris information

A sonar search located the wreckage and defined the limits of the field of debris. The debris was scattered in a rectangle measuring 1.2 km by 525 m. The debris was then identified, mapped and some pieces recovered. All the extremities of the aeroplane were within the identified rectangle: the cockpit, the wings and the tail. These observations, together with the small size of the debris, made it possible to conclude that the aeroplane had collided with the surface of the water under high energy and ruled out the scenario of the aeroplane having broken up in flight.

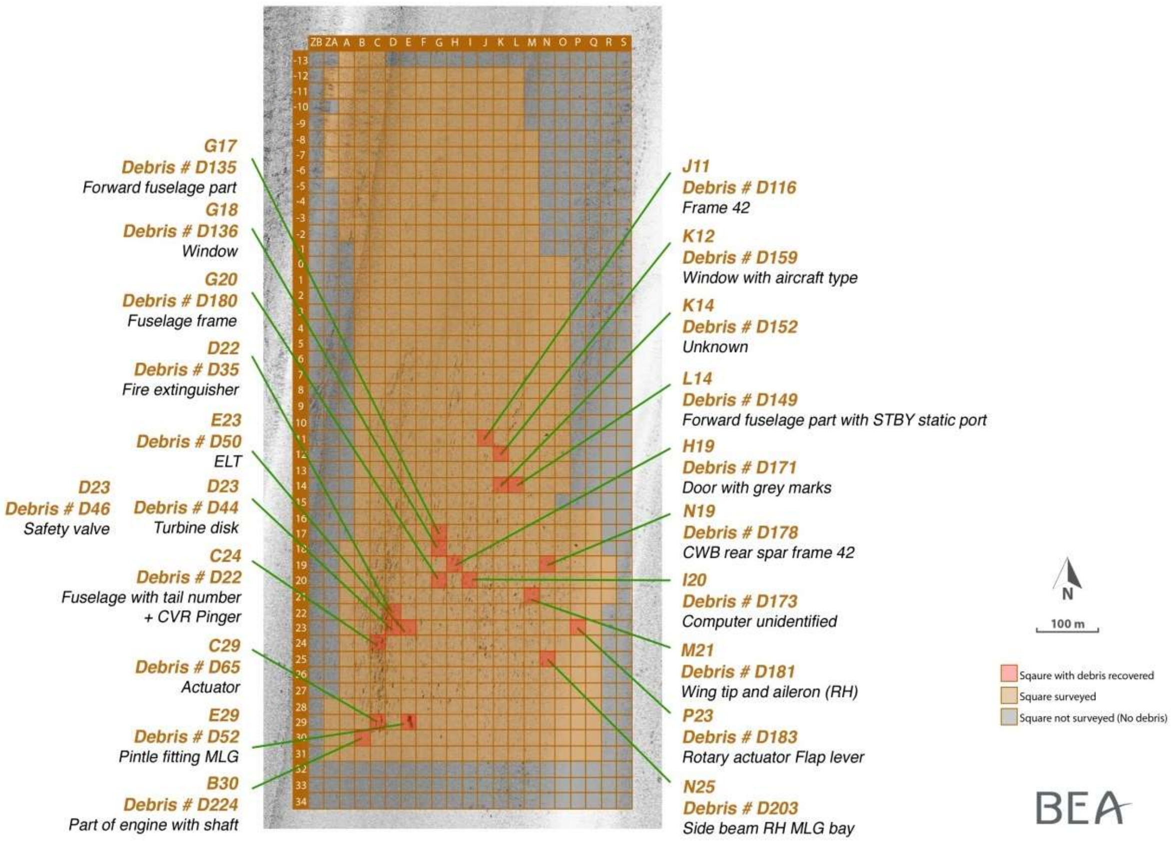


Figure 15: field of debris (source: BEA/EAAID)

Some debris showed signs of having been subject to high temperatures, and traces of soot. In particular, soot was visible on the side of the cockpit between frames 4 and 8 as illustrated in the image below.

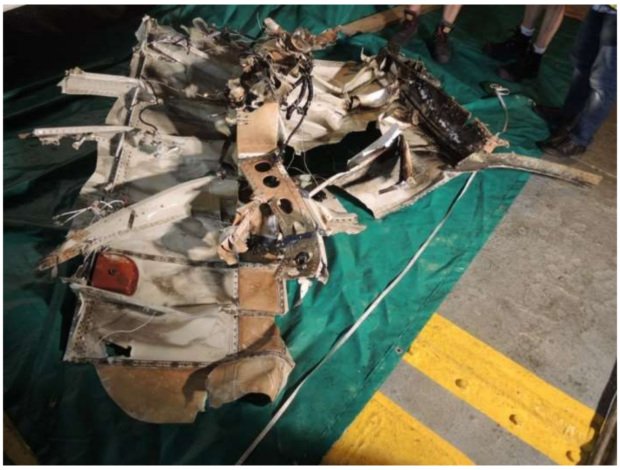


Figure 16: cockpit debris showing black deposits (source: BEA/EAAID)

The figure below roughly shows the corresponding area.

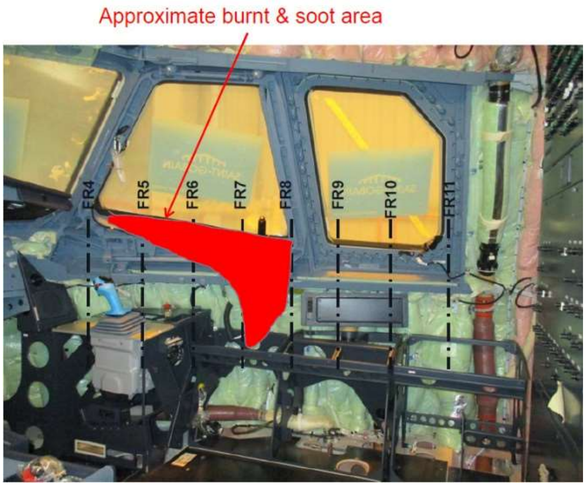


Figure 17: corresponding area on an A320 (source: BEA/EAAID)

4.5 CFR and FDR recording

4.5.1 Current Flight Reports (CFR)

The CFR is generated by the aeroplane's systems. It records the failures or malfunctions of the systems, including the ECAM alerts and maintenance messages. The CFR is used for maintenance purposes and allows the operator to anticipate any maintenance action before the aircraft lands.

The CFR from the flight was recovered by the aeroplane manufacturer and the operator.

It contained the following data regarding the failure/alerts during the cruise phase of the flight.

Time	Message	Message type
00:26	ANTI ICE R WINDOW	ECAM alert
00:26	R SLIDING WINDOW SENSOR	Maintenance message
00:28	R FIXED WINDOW SENSOR	Maintenance message
00:26	SMOKE LAVATORY SMOKE	ECAM alert
00:27	AVIONICS SMOKE	ECAM alert
00:29	AUTO FLT FCU 2 FAULT	ECAM alert
00:29	F/ CTL SEC 3 FAULT	ECAM alert

4.5.2 Flight Data Recorder (FDR)

The FDR ceased operating when the aeroplane was in cruise at FL370. Around seven minutes of flight were not recorded between the FDR ceasing operation and the estimated impact with the water (estimated from the ELT transmission time).

At 00:26:14, the "*LAVATORY SMOKE*" warning was activated. This warning remained active until the end of the FDR recording. In the cockpit, a CRC-type warning (Continuous Repetitive Chime) and the *Master warning* light were activated on the captain's and co-pilot's sides.

The *AVIONICS SMOKE* alert was triggered 46 s later. No specific sound or warning light was associated with this alert.

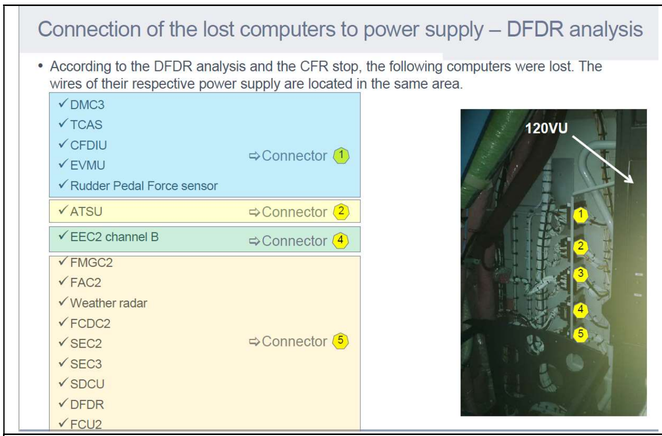
At 00:29:39, the on-board systems disconnected the autopilot. The CRC warning associated with the *LAVATORY SMOKE* warning stopped and the aural warning (*Cavalry charge*) associated with the disconnection of the autopilot sounded twice in the cockpit[22].

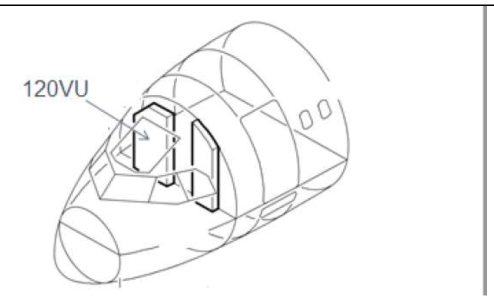
The read-out of the FDR showed that several on-board computers failed successively from 00:29:26 within an interval of 30 s.

The loss of these computers alone does not immediately affect the aeroplane's ability to fly, navigate or send information. At the end of the recording, the aeroplane's flight path and speed were stable.

These computers are located at various points on the aeroplane. However, the power supply cables for these computers are all connected in the same place, in an area at the rear right of the cockpit.

[22] The procedures ask pilots to cancel the warning by pressing the *MASTER WARN* pushbutton or the *Take over pb* on the sidestick.





The area which all the power supply cables run through is located between the cockpit floor and the electrical panel marked "120VU".

Note: The ECAM "ANTI ICE R WINDOWS" alert present in the CFR is not part of the parameters recorded by the FDR.

4.6 Cockpit Voice Recorder (CVR)

4.6.1 Contents

As for the FDR, the CVR ceased operating when the aeroplane was in cruise at FL370. Around seven minutes of flight were not recorded between the CVR ceasing operation and the estimated impact with the water.

The CVR recording is of a total time of 02 h 05 min 26 s. The CVR model equipping SU-GCC stores information from the four input channels in five memory spaces:

- CVR channel 1 (CDB) file: it contains the left-hand pilot's audio signal (radio and interphones) and the signal from his microphones*. The duration of this file is 30 min 30 s.
- CVR channel 2 (COPIL) file: it contains the right-hand pilot's audio signal (radio and interphones) and the signal from his microphones*. The duration of this file is 30 min 30 s.
- CVR channel 3 (3rd/PA) file: it contains the audio signal from the third person (sat on the jump seat behind the co-pilot's seat) (radio and interphones) and the signal from his microphones*. It also contains the exchanges between the cockpit and the cabin (cabin crew) via the cabin interphone. The duration of this file is 30 min 30 s.
- CVR Mix file (MIX): it contains the CVR channel 1 to 3 inputs for a duration of 2 h 05 min 26 s.
- CVR channel 4 file (CAM): it contains the signal from the cockpit area mike. The duration of this file is 2 h 01 min 03 s.

*: headset mike, hand-held mike and oxygen mask mike when the latter is active.

4.6.2 Pick-up sources

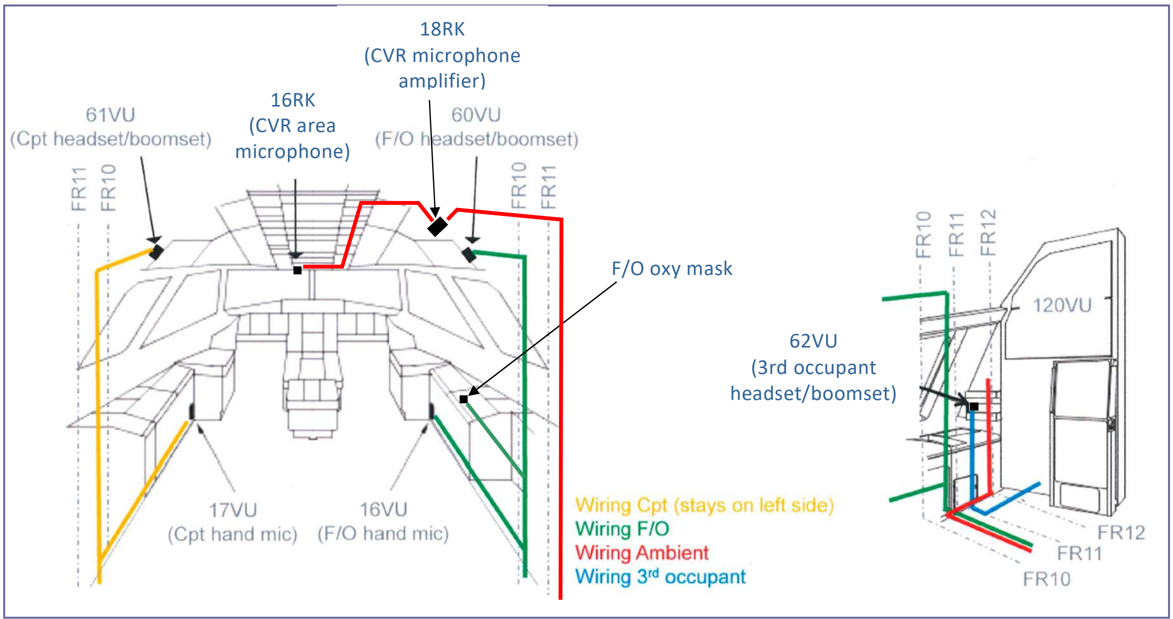
The playback of the CVR and the analysis of the waveforms revealed, shortly after the crew first started mentioning the fire[23], the successive loss of the various pick-up sources supplying the audio-CVR systems.

[23] See paragraph 4.6.5.

UTC	Cumulated time	Events
00:25:30	0	“*Fire!*” call-out by crew
	+4 s	The signal from the co-pilot’s oxygen mask microphone no longer reaches the audio-CVR system
	+17.5 s	The signal from the co-pilot’s headset microphone (boom mike) no longer reaches the audio-CVR system
	+1 min 11 s	The signal from the third person’s headset microphone (boom mike) no longer reaches the audio-CVR system
	+2 min 03 s	The audio signal from the CAM/microphone and/or CU channel starts to degrade
	+3 min 30 s	The signal from the CAM/microphone and/or CU channel no longer reaches the CVR
	+4 min 24 s	End of CVR recording

Note: the captain’s boom mike continued to operate without any noticeable degradation in its audio pick-up and thus picked up part of the background noise up to the end of the CVR recording.

The view below shows the routing of the electrical harnesses that carry the audio signals in the cockpit to their respective systems (AMU and CVR):



(Source: BEA based on AIRBUS

Figure 18: route of electrical harnesses associated with CVR on an A320

4.6.3 Use of headsets and ATC communications

Each pilot has the necessary set of equipment for his/her exchanges. This consists of several microphones along with interface and selection units. Refer to the appended Functional description of the Audio-CVR system.

In commercial air transport operations, the operational procedures recommend that pilots wear their headsets and use the headset boom microphone when the aircraft is below FL100. During cruise, radio and interphone activities (exchanges with the cabin) are monitored by the PM by listening to his loudspeaker; voice messages are generally transmitted using the hand-held microphone.

A detailed analysis of the audio content of the two CVR channels allocated to each of the pilots revealed that the pilots of flight MS804 had not been wearing their headsets since the start of the CVR recording. During the last two hours of the recording, radio communications were mainly made by the captain via the hand-held microphone; two were probably made by the co-pilot via the hand-held microphone.

The audio analysis of the co-pilot's CVR channel revealed a "cavernous" background noise characteristic of the pick-up by the oxygen mask's internal microphone from the beginning of the CVR recording. This microphone is located inside the oxygen mask, in the visor support, at the base of the regulator which delivers the ambient air and oxygen mixture to the pilot.

The sound picked up by the oxygen mask microphone had an acoustic signature consisting of the emergence of five characteristic noise bumps The appendix Sound pick-up by the oxygen mask microphone presents the comparison made with a series of audio samples taken from the BEA's audio database. The spectral view below shows the comparison between the signal recorded by the captain's CVR channel and that recorded by the co-pilot's CVR channel.

The low-frequency noise bump (from 100 to 500 Hz) and the four broadband bumps (780 Hz, 1300 Hz, 2090 Hz and 2640 Hz) confirmed that the microphone of the co-pilot's oxygen mask was active.

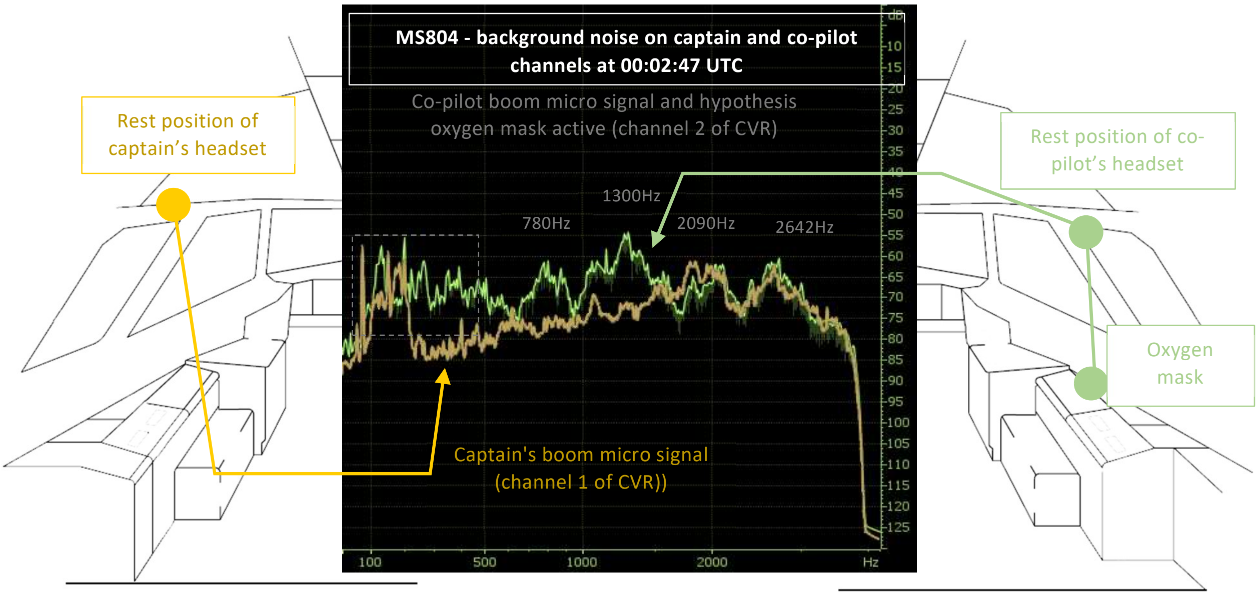


Figure 19: comparison of noise spectrum picked up by captain's and co-pilot's boom mikes

Findings-Intermediate conclusion
The co-pilot's oxygen mask microphone was active during the last 30 min of the CVR recording, and most likely from the start of the CVR recording.

The CVR input channels, which are dedicated to recording conversations, radio communications and the pilots' audio signals, receive a composite signal that is the result of mixing by the on-board audio source management system. The appendix, Functional description of audio-CVR system sets out the on-board audio system.

The audio system routes the signals picked up by the various microphones to the transmission source(s) (i.e. the selected radio, the intercom, the loudspeaker, etc.). This routing is based on priority rules. One of these rules defines the following priority for the "radio" function:

- hand-held microphone;
- oxygen mask;
- pilot's headset microphone (boom mike).

In this case, the continuous activation of the co-pilot's oxygen mask microphone meant that he could not use his boom mike to transmit radio messages. The aircraft was in cruise from the start of the CVR recording; the pilots were no longer using their respective boom mikes.

Findings- Intermediate conclusion
The co-pilot's boom mike could not be used to transmit radio communications for the last thirty minutes, and most probably for the last two hours. The co-pilot, as PF on the flight, did not need to use his boom mike before reaching FL100 and used his hand-held microphone when needed during the cruise. Therefore, the co-pilot had no opportunity to detect that his boom mike was inoperative. This explains why the activation of the mask's microphone might not have been detected.

With a normal operating pressure in the system, the activation of the oxygen mask microphone may have been due to:

- the oxygen mask storage box having been manipulated. The mask storage box might have been opened and not reset. The reset is a normal part of the test procedure before every first flight of the day;
- a faulty or incorrectly set microphone activation switch.

The manufacturer of the mask and oxygen box indicated that it was also possible that overpressure in the supply system could place and maintain the storage box in the unreset position. However, the manufacturer pointed out that the overpressure required to move the piston is greater than the overpressure which would lead to an uncontrolled flow through the mask regulator.

4.6.4 Analysis of CVR conversations

The voice recording (area microphone and headset boom microphones) by the CVR only gives a partial view of the activity in the cockpit, of communications with the exterior (traffic control or operations) and of communications between the flight and cabin crew members. This must be taken into account when drawing conclusions based on the interpretation and translation of the audible speech on the CVR recordings.

4.6.4.1 Context prior to the accident sequence

The CVR recording of flight MS804 contains the 02 h 01 min 04 s of the last exchanges in the cockpit. The discussions between the crew members (between cabin crew and/or between cabin crew and flight crew) were in Egyptian Arabic. At the start of the recording, the aircraft was in cruise. ATC communications were mainly from the captain. There was constant background music in the cockpit. The cabin crew were looking after a sick passenger whose state of health was deteriorating (faintness). In the first hour of the recording, this event led to the cabin crew going in and out of the cockpit a large number of times in order to inform the captain of the evolution of the passenger's state of health. In the second hour of the recording, a cabin crew member took a seat in the cockpit and the conversations no longer concerned the management of the flight. Forty minutes before the end of the recording, the crew had a meal.

In the last ten minutes of the CVR recording, the captain asked a cabin crew member for a blanket and a pillow. Once these items had been provided, this cabin crew member left. At this point, the two pilots and the first cabin crew member were present in the cockpit.

4.6.4.2 Elements relating to smoking in the cockpit

On 26 April 2022, an Italian media[24] published information presented as a summary of a confidential report drawn up by experts appointed by the French courts. The report stated that there had been the sound of an oxygen leak in a pilot's oxygen mask and that "a spark or flame had started a fire", adding that a lit cigarette could have been the cause of the fire. The Italian article noted that the report mentioned that cigarettes were frequently used on this aeroplane, since the ashtrays had recently been replaced.

The preliminary CVR playback work carried out by the BEA mentioned the presence of a phrase initially translated from Arabic as follows: "blow smoke on me"; this phrase could potentially reflect the action of smoking by one of the crew members.

Additional work involving seven Arabic-speaking linguists - two of them native Egyptians - was carried out in order to have an in-depth analysis of the content of the recorded conversations. The aforementioned phrase was corrected and its translation modified as follows: "he fainted" or "he felt unwell", probably referring to the ill passenger. This phrase precedes a discussion between the two pilots about the possibility of diverting to Athens or Albania.

A second phrase later on could potentially refer to the smoking habits of one of the two pilots: "Have you stopped smoking [or what/not], I can't smell [the smoke/smell]?”

In conclusion, none of the speech components heard in the conversations recorded by the CVR clearly mentioned the crew's intention to smoke or that they were smoking.

Findings- Intermediate conclusion
No evidence from the cockpit voice recording confirms or refutes the hypothesis that people were smoking in the cockpit.

4.6.5 Audio description of accident sequence

Conversations/voices/speech during the accident sequence

At 00:25:23, a loud hissing lasting 2.6 s could be heard on the CVR recording. This noise is considered to be the start of the accident sequence (referred to as "*T0*").

At this point, the captain called out to the co-pilot just before a loud transient noise was heard,

[24] https://www.corriere.it/cronache/22_aprile_26/volo-egyptair-incendio-piloti-fumo-fb725f4c-c4d3-11ec-8db2-dfe15c68e9dd.shtml

immediately followed by a hissing sound, a sound runaway phenomenon[25] and a continuous leaking noise[26].

The crew mentioned the words "fire" and "extinguisher" several times. Short coughing fits and voiced sounds (unintelligible words or phrases) were emitted shortly afterwards. The noise level of the continuous leak gradually decreased, making it possible to perceive crackling noises and to detect the ambient music again.

A succession of aural warnings were audible on the CVR recording; these consist mainly of the MASTER WARNING, SMOKE DETECTOR and CAVALRY CHARGE warnings 15 s before the end of the CVR recording.

Waveforms and key events
The appendix Waveforms of the CVR recording graphically presents the CVR content and chronologically describes the succession of different sound events during the last five minutes of the CVR recording.

The view below shows an extract lasting one minute, of the beginning of the accident sequence. The various events (noises, sounds, crew call-outs, etc.) are called EVT1 to EVT9 For the most part, the events are in the 18 s that followed the first flow noise (EVT2).

[25] Presence of noise bumps - broadband energy bumps - where the frequency increases rapidly to concentrate around 1.2 and 2 kHz (the phenomenon could be described in psychoacoustic terms as a "hissing sound increasing in pitch"). The sound runaway is accompanied by an increase in the overall noise level.
[26] Broadband noise over the entire bandwidth of the microphone picking up the sound.

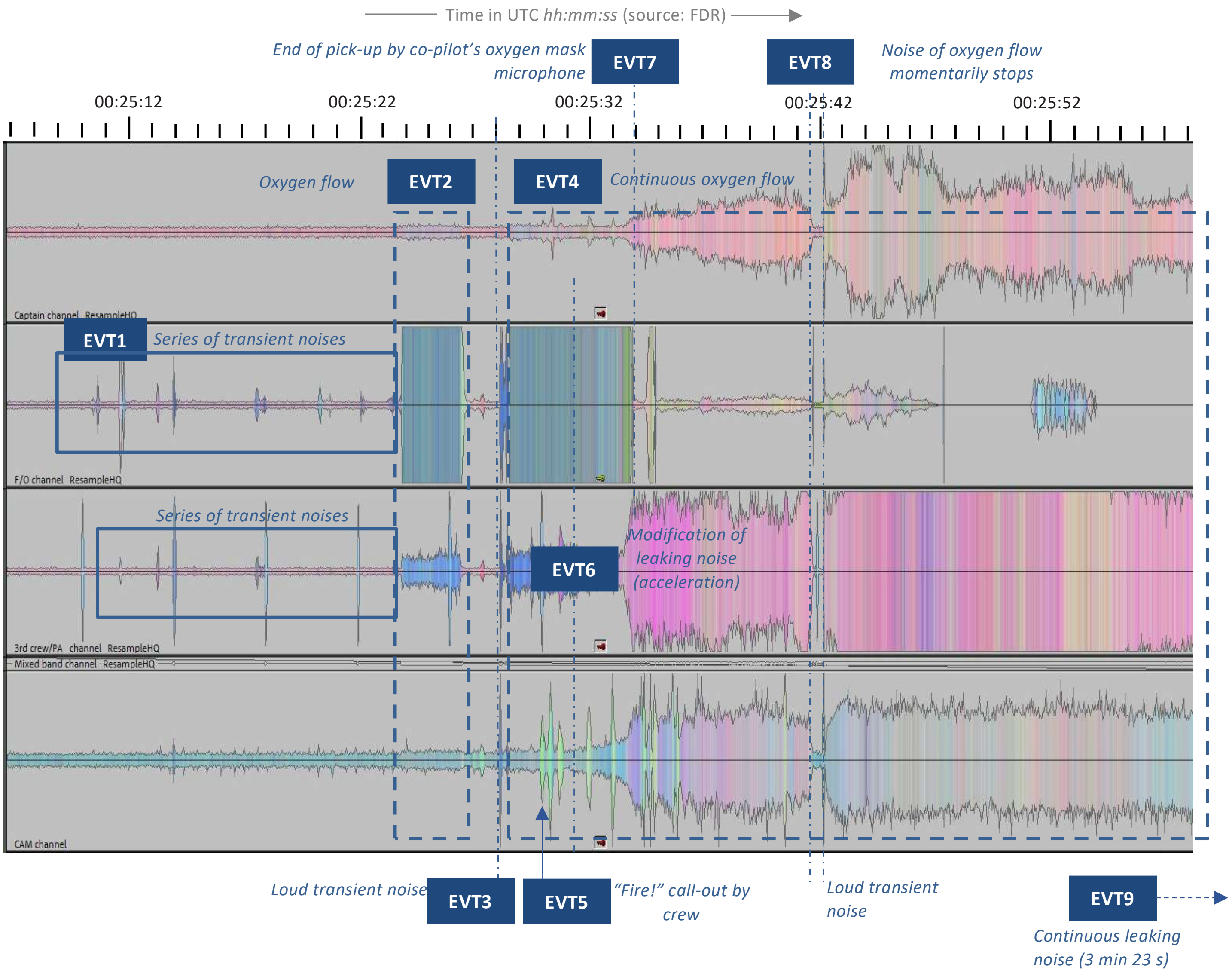


Figure 20: sequence of aural events - chronological detail (view of waveform – source: BEA)

The nine sound events in question are the following:

- EVT1 Numerous transient noises were present on the co-pilot CVR audio channel and to a lesser extent, on the third person/PA channel;
- EVT 2 A very loud, short (2.6 s) leaking noise is recorded on the co-pilot's CVR audio channel. The start of the leaking noise constitutes T0 of the event sequence;
- EVT 3 A loud transient noise is heard at T0 + 4.3 s;
- EVT 4 A continuous leaking noise starts (and will last more than 3 min) at T0 + 4.7 s;
- EVT 5 First "fire" call-out at T0 + 6.1 s;
- EVT 6 Modification of continuous leaking noise at T0 + 7.6 s;
- EVT 7 Loss of signal from co-pilot's oxygen mask microphone at T0 + 9.6 s;
- EVT 8 Leaking noise stops for a short time at T0 + 17.9 s (duration: 0.5 s);
- EVT 9 End of leaking noise at T0 + 3 min 23 s: the noise level of the leak continues to decrease until it disappears into the background noise of the cockpit.

4.7 Tests and research

4.7.1 Description of tests and research

Tests and research were carried out to identify the nine isolated sound events in the accident sequence.

These tests were carried out on the BEA's premises and on the premises of the manufacturer of the oxygen system. The principal test resources were:

- a mobile CVR system to record the audio pick-up by a CAM and two boom microphones;
- a cockpit oxygen distribution system.

4.7.2 EVT1: Transient noises on the co-pilot's audio channel

The series of transient noises recorded on the co-pilot's channel corresponds to the mix of the pick-up by the mask microphone and the co-pilot's headset.

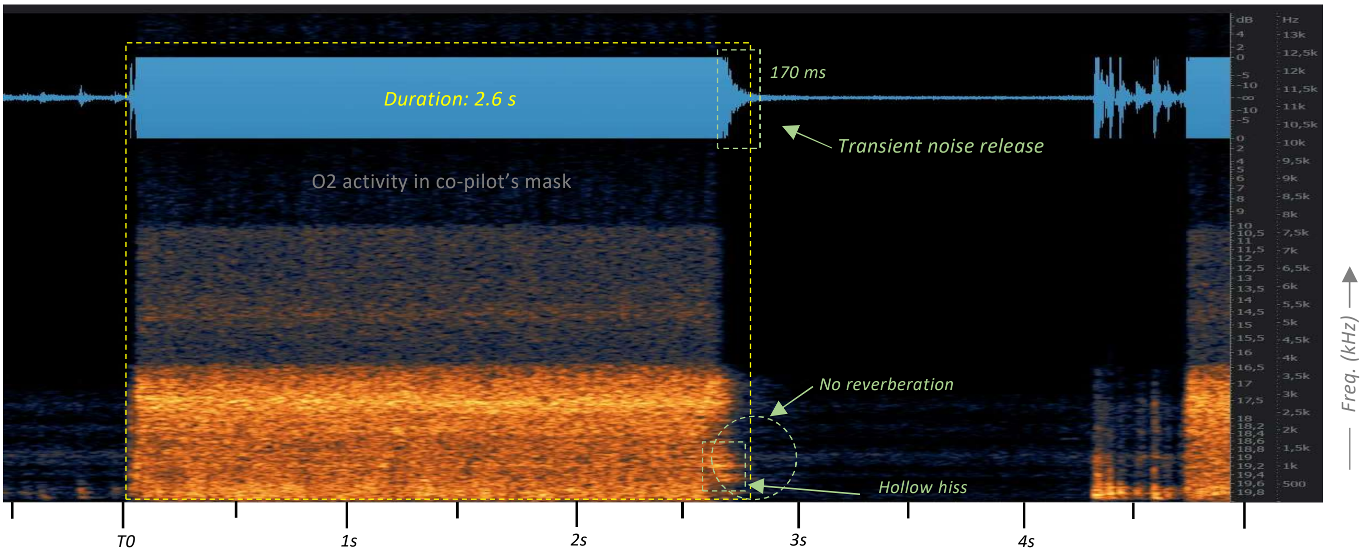
Some of these transient noises are present with a lower amplitude on the 3rd person's channel. They are barely detectable on the CAM channel. Based on the measurements carried out in a cockpit (see appendix EVT1), these transient noises correspond to elements being moved close to the document storage compartment.

Tests in the cockpit also showed that the noise of elements being moved were broadcast by the co-pilot's loudspeaker and that they were perceptible from the co-pilot's seat. However, these same events were picked up to a small extent or not at all by the CAM microphone (with the exception of the loud events).

Findings - Intermediate conclusion
For the duration of the CVR recording, the co-pilot's oxygen mask microphone picked up low sound transient noises of elements being moved close to the document storage compartment. This pick-up could be heard on the co-pilot's loudspeaker (depending on the volume selected).

4.7.3 EVT2: A very loud, short (2.6 s) leaking noise recorded on the co-pilot's CVR audio channel

The following figure shows the analysis of the EVT2 from an acoustic point of view. In blue, the waveform represents the amplitude of the noise as a function of time. The band in shades of orange represents the distribution of the frequency as a function of time.



T0 = 00:25:22 UTC (ref. FDR data)

Figure 21: first oxygen flow activity in co-pilot's mask (spectral view – source: BEA)

This sequence was compared with various sound recordings made during the handling of oxygen masks and mask storage boxes (see appendix EVT2).

The duration of the transient noise release (170 ms) corresponds to the end of pressurisation to 5 bar of all the hoses upstream of the regulator:

- this is the case when the mask is not in the *EMERGENCY* configuration and the test pushbutton on the door of the oxygen mask storage box is pressed;
- or when the box is not reset after pressing the *EMERGENCY* knob.

The absence of a reverberation indicates that there is no bleed and corresponds to a box with identical pressure in all the hoses, and therefore not reset.

The leaking noise lasts much longer than that created by pressing the test pushbutton on the mask storage box door (observed between 700 and 900 ms during tests carried out in the laboratory and on aeroplanes in service).

The leaking noise lasting 2.6 s which starts at t0 corresponds to an oxygen flow via the oxygen mask regulator; it is comparable to that produced by pressing the mask *EMERGENCY* knob when the box has not been reset.

In addition, the hollow hiss indicates that the dilution control on the co-pilot's mask was in the 100% oxygen position.

Findings - Intermediate conclusion

The co-pilot's oxygen mask was not in the permanent *EMERGENCY* position before t0, start of the oxygen flow sound.
The dilution control on the co-pilot's oxygen mask was in the 100% position.
The storage box for the co-pilot's oxygen mask was not in the reset position.
A flow of oxygen via the co-pilot's mask lasting 2.6 s began at 00:25:30 (t0).
The flow is equivalent to that caused by pressing the *EMERGENCY* knob on the mask.

The information available in the scope of the investigation does not make it possible to determine if the oxygen flow was the result of a human action on the *EMERGENCY* knob, whether it be unintentional or intentional.

- Unintentional action

  It seems unlikely that there was an unintentional action on the knob, partly because the knob was pushed for 2.6 s, and partly because of the relative difficulty of accessing the knob (the knob is protected by the hose which passes over it). Moreover, in flight, the cover is normally closed on the mask storage boxes[27].

- Intentional action

  One possible explanation is that the co-pilot was alerted by the noises emitted on the loudspeaker from the moving of elements nearby, picked up by the microphone of the oxygen mask. At this time, the noise level in the cockpit was low compared with the previous period. In addition, the captain wished to rest and although the CVR contained no mention of a transfer, he might have passed communications to the co-pilot, who might have increased the volume of the loudspeaker. It is possible that the co-pilot then performed actions corresponding to the mask test procedure. In the darkness of the night flight, with the seat forward in the PF's position, this action may have simply been to press the *EMERGENCY* knob on the mask; pressing the pushbutton on the box being more difficult to do. No mention of a coordination for such an action is present on the CVR.

No "oxygen" activity was recorded by the CVR before t0 - i.e. no intentional handling of the personal oxygen device, or noise characteristic of a leak. No pilot "oxygen" activity (donning and normal use of a cockpit oxygen mask) was recorded by the CVR after t0. The only element linked to the cockpit oxygen system is the continuous leak mentioned above.

Findings-Intermediate conclusion

There was no mention of any intention or action on the part of either of the pilots to use the personal oxygen devices.

4.7.4 EVT3: Loud transient noise

A loud transient noise occurred at t0 + 4.3 s. It was clearly picked up by the co-pilot channel, to a lesser extent by the 3rd person channel and to an even lesser extent by the CAM. These differences indicate that the co-pilot's mask was in the storage box. The source was not identified.

[27] There was no evidence to determine whether or not this was the case for flight MS804.

Findings-Intermediate conclusion
An event leading to a loud transient noise of unknown source occurred in the co-pilot's mask storage box 4.3 s after the start of the first flow of oxygen in the mask (t0 + 4.3 s).

4.7.5 EVT4 and EVT9: continuous leak

A cockpit oxygen cylinder was completely emptied in a laboratory several times by creating a continuous oxygen leak (see Appendices EVT4 and EVT9).

The oxygen leak produced by the rupture of a hose, either upstream of the mask storage box or at the hose connecting the mask to the box, generated a broadband noise lasting several minutes, the sound level of which decreased progressively when a remaining pressure of less than 20 bar in the oxygen bottle was reached.

The tests confirmed that the long gas flow noise present on the CVR recording of flight MS804 corresponded to a continuous leak from the cockpit oxygen system. The acoustic signatures recorded during these tests seem to attribute the leak to a rupture in the oxygen supply in the box, upstream of a mask, as being more likely than a leak upstream of the mask storage box.

The continuous leaking noise did not give rise to a sound runaway as is the case on the recording of flight MS804 (EVT6).

The time taken for the O2 cylinder to completely empty on flight MS804 is well below the theoretical value calculated by the equipment manufacturer (11 min). Several hypotheses can be envisaged:

- either the theoretical value is overestimated;
- or the flow rate in the event is greater than that obtained with a pressure of 5 bar[28];
- or the cylinder was not very full.

Findings-Intermediate conclusion
There was a continuous uncontrolled leak lasting 3 min 23 s in the co-pilot's mask storage box corresponding to the complete emptying of the oxygen cylinder (start at t0 + 4.7 s).

4.7.6 EVT8: interruption of leaking noise

The leaking noise was observed to stop for 0.6 s at t0 + 17.9 s. Tests were carried out to try and reproduce this break by twice pressing the CREW SUPPLY ON pushbutton on the overhead panel.

Tests on a reproduction of the A320 oxygen system and on several aeroplane of the same type showed that the controlled cut-off using this pushbutton lasted a minimum of 0.9 s. Details of the tests are given in appendix EVT8.

Pressing this pushbutton is the only way for the crew to cut off the oxygen supply. The observed break in the leak was not linked to a crew action.

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[28] In the event of overpressure upstream of the oxygen bottle pressure regulator (or in the oxygen bottle) and with a pressure regulator operating as per design, a valve evacuates the oxygen to the outside of the aircraft. In the time taken in such a scenario, the mask storage box can be activated, resulting in the mask having a continuous or temporary leak.

Findings-Intermediate conclusion
The break in the oxygen leaking noise (at t0 + 17.9 s) lasting 0.6 s was not linked to a crew action.

4.7.7 Cockpit door open or closed

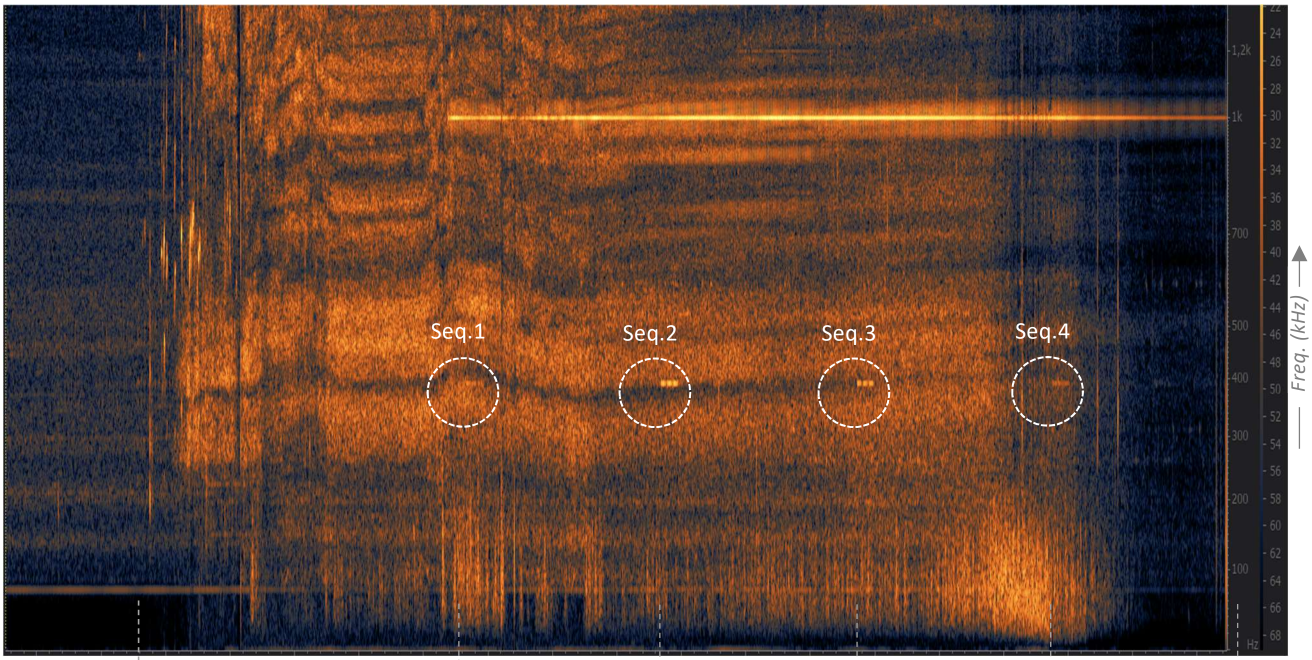


Figure 22: Lavatory Smoke warning sequences (*triple low chime*) - (spectral view)

The "triple low chime" corresponding to the "Lavatory Smoke" warning can be perceived on the CVR (first transmission at 00:26:17 i.e. t0 + 47 s) via the CAM channel. This signal was generated on the cabin loudspeakers every thirty seconds. The next three transmissions are also perceptible; the CAM was then too damaged to pick them up.

A 10 dB increase in the "triple low chime" signal was measured for sequences 2 and 3. This increase was compatible with the warning being picked up when the cockpit door was open (see appendix, Lavatory for details). Sequences 1 and 4 were therefore very likely picked up with the door closed.

In addition, a noise that could correspond to the cockpit door being used could be heard at 00:26:46.

Findings-Intermediate conclusion
When the "Lavatory Smoke" warning first sounded, i.e. 47 s after the start of the event at 00:26:17, the cockpit door was closed. It was then in the open position (at 00:26:48 and 00:27:18, potentially continuously over this period) before being closed again.

When the continuous leaking noise ceased - or reached such a low level that it disappeared into the cockpit background noise - the background music in the cockpit reappeared, the CRC aural warning ceased and the autopilot disengagement aural alert was triggered. A that time, no movement or door opening noise are perceptible on the CVR. The cockpit door appeared to be closed at this point.

Findings-Intermediate conclusion
The cockpit door was most likely closed when the autopilot was disengaged and the CVR stopped operating at 00:29:54, i.e. t0 + 4 min 24 s.

4.7.8 Disconnection of autopilot

At 00:29:39, the aural warning (Cavalry charge) associated with the disconnection of the A/P sounded twice in the cockpit.

The procedures ask pilots to cancel the warning by pressing the *MASTER WARN* pushbutton or the *Take over pb* on the sidestick.

Findings-Intermediate conclusion
The data recorder did not record any change in parameters that could result from an action by the crew after the autopilot was disconnected.

5. OXYGEN FIRE STUDY

Note: The aim of the study is twofold: to study certain phenomena, and in particular to record the noise produced, in order to validate or invalidate hypotheses concerning the accident scenario for flight MS804, and to learn more about fires in the presence of oxygen in the cockpit. For this reason, the scope of the study covers wider accident scenarios than the potential ones of the SU_GCC accident. The fact that batteries and cigarettes, for example, were chosen as external ignition sources does not mean that they are considered the most likely ignition sources. In the same way, the effects of halon are studied without the conclusions being directly transposed to flight MS804. Conclusions specific to flight MS804 are set out in chapter 5.6.

5.1 Introduction

A fire is defined as the combustion of a fuel by oxygen and occurs when oxygen, fuel and heat combine to create a self-sustaining chemical reaction.

The chemical reaction is an oxidation of hydrocarbons. When wood, paper, oil or gas burn, for example, it is the hydrocarbons making up the materials that oxidise during combustion.

The oxidation reaction has to be initiated by the addition of heat. Since oxidation releases heat, the reaction sustains itself over time.

The pressure and concentration of oxygen affect the flammability of a material. The greater the quantity of oxygen present, the easier it is for the material to ignite, the faster and more extensive the combustion and the higher the temperatures.

The presence of the oxygen distribution system has a twofold impact:
(1) the air may become enriched with oxygen in the vicinity of the supply system; the presence of oxygen makes the elements more flammable and the start of a fire more likely;
(2) a fire that damages the oxygen systems, if it causes a hose to rupture, becomes an oxygen-enriched fire that is difficult to control.

The cockpit oxygen system is therefore particularly critical and must be resistant to various ignition mechanisms (both internal to the system and external) to prevent it contributing to a fire in the cockpit.

Full-scale tests were carried out to study:

- certain ignition mechanisms likely to affect the cockpit oxygen system;
- the spread of an oxygen-fed fire;
- the means to extinguish an oxygen-fed fire available in the cockpit.

The tests were organised with the help of the oxygen equipment manufacturer, using equipment from dismantled aircraft, on the INERIS's[29] premises.

[29] Institut national de l'environnement industriel et des risques (French National Institute for industrial and environmental risks).

5.2 Starting a fire affecting the oxygen system

The following ignition mechanisms were studied:

- impact of an external heat source;
- internal ignition of the hoses by:
  - creation of a spark,
  - particle impacts,
  - electrostatic discharge;
- ignition of grease and dust in the vicinity of the device, which may be enriched with oxygen.

5.2.1 External heat source

The certification requires the oxygen system to be designed and installed in such a way that the impact of an external ignition source is minimised. Note, by convention in this document, external ignition mechanisms are defined as elements outside the oxygen system, i.e. elements originally outside the mask storage boxes.

Two potential external sources of heat were selected and tested:

- a lithium battery from an electronic device (smartphone, tablet, electronic cigarette);
- a glowing cigarette.

5.2.1.1 Lithium battery tests

The aim of the tests was to study the thermal runaway of lithium batteries, used in electronic equipment, and their capacity to damage the oxygen system.

In flight, electronic equipment such as smartphones, tablets and electronic cigarettes may be placed on the cockpit structure or in the document storage compartments on the sides of the cockpit, close to the oxygen masks.

Figure 23: aeroplane document storage compartment (here Airbus A320)

During the tests, the smartphones, electronic cigarettes and tablets were placed on a hot plate that could reach a temperature of 400°C, causing a thermal runaway in the internal batteries. The equipment was tested either in a free field (on a block of cellular concrete) or in an aeroplane document storage compartment. The temperature of the hot plate was gradually increased until there was thermal runaway in the equipment's battery.

Eight tests were carried out in total:

	Tested equipment	Position
Lithium battery_01[30]	Smartphone	Free field
Lithium battery_02	Smartphone	Free field
Lithium battery_03	Smartphone	Document storage compartment
Lithium battery_04	Tablet	Free field
Lithium battery_05	Tablet	Document storage compartment
Lithium battery_06	Electronic cigarette	Free field
Lithium battery_07	Electronic cigarette	Free field
Lithium battery_08	Electronic cigarette	Document storage compartment

During the tests, the thermal runaway of the batteries was visually characterised by a sudden release of thick white smoke. No sudden loud sound (snapping, detonation) was produced; only a whooshing sound or hiss could be heard during the ejection of gases. The ejection of incandescent particles was often observed during these tests, but the combustion of these particles proved to be very rapid and insufficient to spread the fire to the environment. The runaways were all preceded by the release of smoke over several minutes.

Figure 24: example of release of smoke during thermal runaway of battery (Lithium_Battery_04 test)

[30] The videos of these tests are provided with the document.

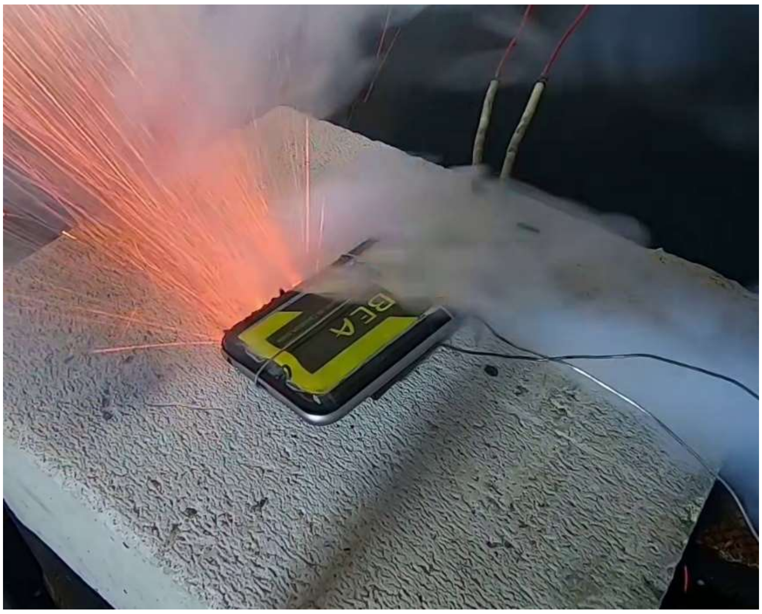


Figure 25: ejection of incandescent particles during thermal runaway of battery (Lithium_Battery_02 test)

The appearance of flames was observed only once, during a test carried out on an electronic cigarette in the free field (Lithium battery_07 test). It is likely that the fire broke out due to the presence of adhesive tape affixed[31] to the body of the cigarette, which burst into flames during the test.

Figure 26: visible flames during Lithium_Battery_07 test

In the conditions of the tests, only one element external to the electronic cigarette (adhesive tape) probably contributed to the outbreak of fire after the thermal runaway of the battery.

[31] This adhesive tape had been affixed by the BEA for the needs of the test.

It is possible that some of the electronic equipment items tested were fitted with batteries protected by a system of pressure relief valves that release the gases if the battery swells; this system prevents spontaneous combustion of the gases.

Tablets are generally equipped with high-capacity batteries. Their internal architecture is often made up of several small battery modules (three in the case of the tablets tested). As a result, the thermal runaway of a tablet is no more violent than that of a smartphone or electronic cigarette; the event is broken down into a succession of thermal runaways corresponding to each of the battery modules.

During the tests carried out on the equipment placed in the document storage compartments, no outbreak of fire was observed. Only the release of dense white smoke was seen.

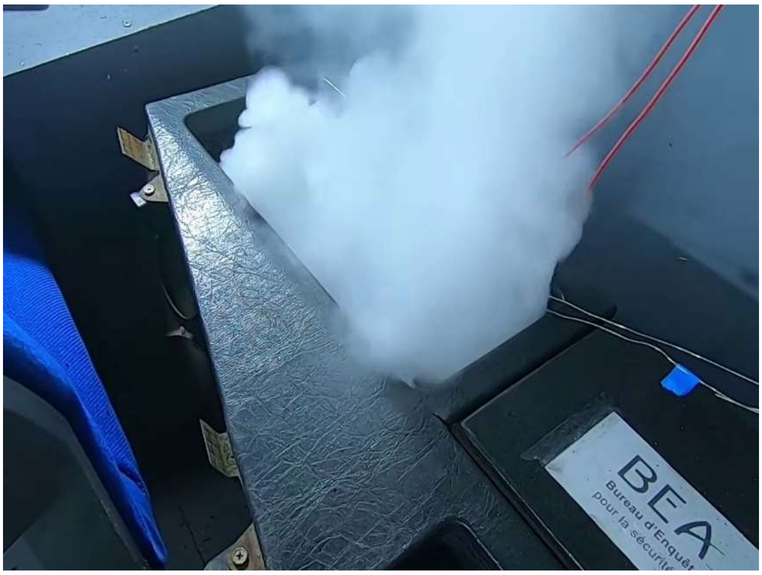


Figure 27: release of smoke during Lithium_Battery_05 test

Several thermocouples were installed to measure the temperature of the hot plate, the temperature of the battery[32] and the temperature at various points in the volume surrounding the electronic equipment.

The temperature curves are shown in the graphs below.

[32] A single thermocouple was placed on the battery. The temperature value measured does not necessarily represent the maximum temperature of the battery.

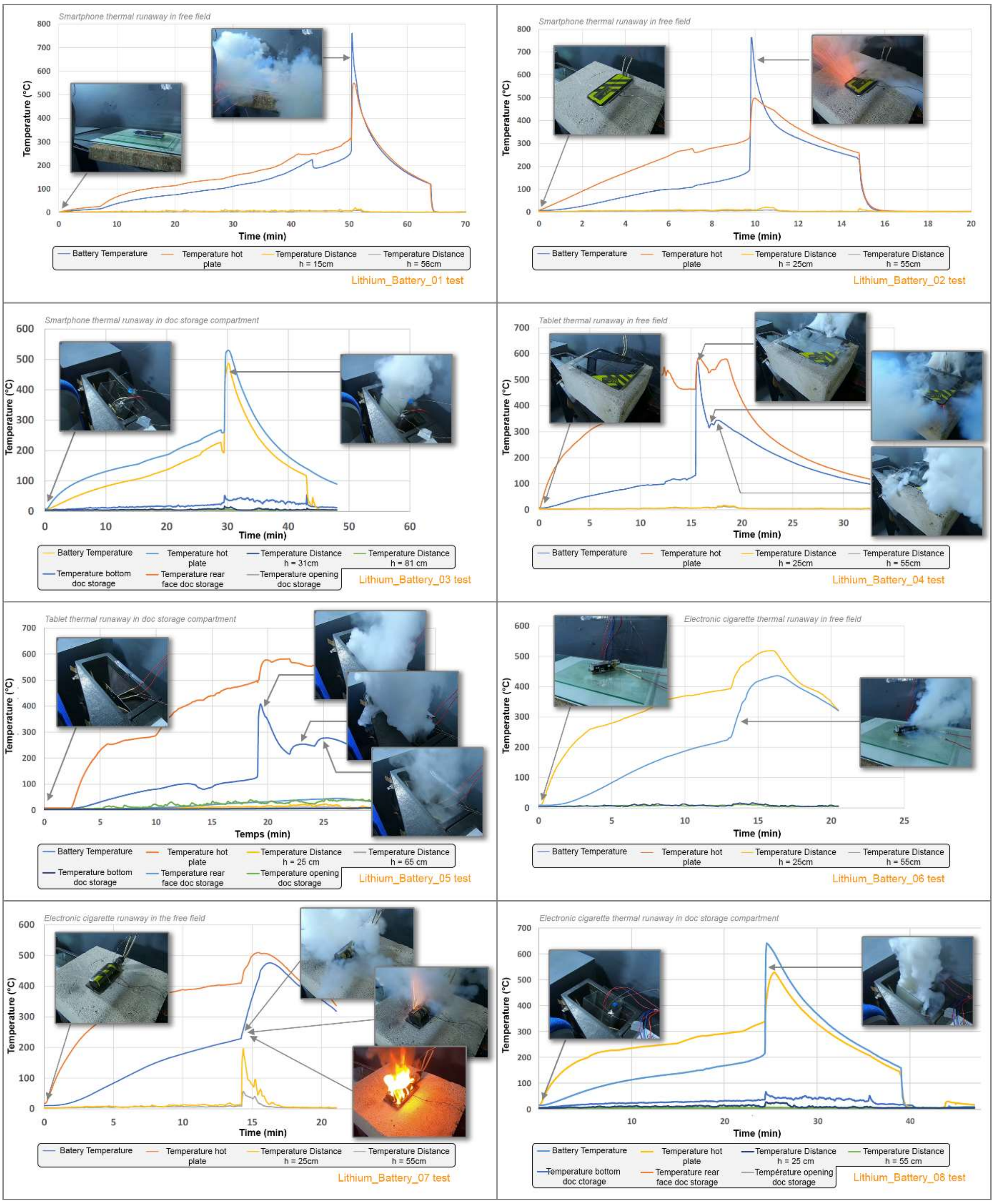


Figure 28: temperature curves - Lithium battery tests (source: BEA - INERIS)

Thermal runaway occurred at battery temperatures of between 100°C (tablets) and 250°C (smartphones), depending on the device. The battery temperature then rose almost instantaneously to an average of 550°C, with values as high as 750°C (in the case of smartphones). No significant rise in temperature in the air surrounding the batteries was measured. During tests carried out in the document storage compartment, the temperature inside the compartment rose without exceeding 50°C.

Only one rise in temperature was observed in the environment (approx. 200°C at a distance of 25 cm and approx. 50°C at a distance of 55 cm), during the Lithium battery_07 test when the tape on the electronic cigarette caught fire.

From a psychoacoustic point of view, the sound produced by the thermal runaway of a lithium battery was similar to a medium to low level whooshing sound. The whooshing sound lasted between 1.5 and 4 s according to the equipment tested. Its tonality varied over time and the whooshing sound was sometimes associated with light hissing.

CONCLUSION

In the conditions used for testing the lithium batteries in electronic equipment, the thermal runaway of a battery resulted in the sudden release of dense white smoke with a sharp and rapid rise in its temperature, without any significant transfer of heat to the surrounding environment. The incandescent particles ejected did not have sufficient thermal energy to ignite the materials. The only outbreak of fire observed was caused by the adhesive tape affixed to an electronic cigarette igniting.

5.2.1.2 Handling a glowing cigarette

5.2.1.2.1 Test on box without presence of external oxygen

The aim of the test was to study the resistance of an oxygen mask hose to a glowing cigarette. The test corresponded to the scenario of a glowing cigarette falling into the oxygen maskstorage box.

Test sequence:
A glowing cigarette was brought into contact with the hose of an oxygen mask. The oxygen pressure in the hose was 5 bar and the whole system was placed in ambient air.

The cigarette went out after about ten seconds. The braided outer protection of the hose and its core (a flexible silicone tube) were not damaged or impaired.

Thus, in the test conditions, a glowing cigarette placed in an open-air enclosure in contact with a pressurised oxygen hose did not damage the system or start a fire. The absence of damage is consistent with the certification, which requires equipment manufacturers to use fire-resistant materials to limit the outbreak and spread of fires.


Figure 29: open-air test (source: BEA)

5.2.1.2.2 Tests on oxygen-enriched boxes

There are several sources of occasional oxygen enrichment of the mask storage box when in service. An oxygen leak from the oxygen mask and storage box assembly is tolerated by the manufacturer (a few millilitres per minute and accumulation of oxygen in the oxygen mask storage box). In addition, the crew must test the oxygen supply to the masks when preparing the flight.

It is therefore possible for the mask storage box to be accidentally or occasionally enriched in oxygen. Oxygen is heavier than air, which is mainly composed of nitrogen, and concentrates in the bottom of the box, which is relatively airtight.

Tests involving the handling of glowing cigarettes were carried out in boxes enriched by oxygen on pressing the *EMERGENCY* knob on the mask regulator. When the *EMERGENCY* knob was pressed, an increase in oxygen concentration of 2 to 3 % per second was measured in the mask storage box.

For each of the tests, a mask storage box with a glass panel was used; the glass surface made the inside of the box visible so that the sequence of events produced by potential damage to the oxygen mask and storage box assembly could be observed.

An oxygen mask and its hose holding oxygen under a pressure of 5 bar were placed in the box. A glowing cigarette attached to the end of a pole was handled near the box and then the cigarette was dropped inside.

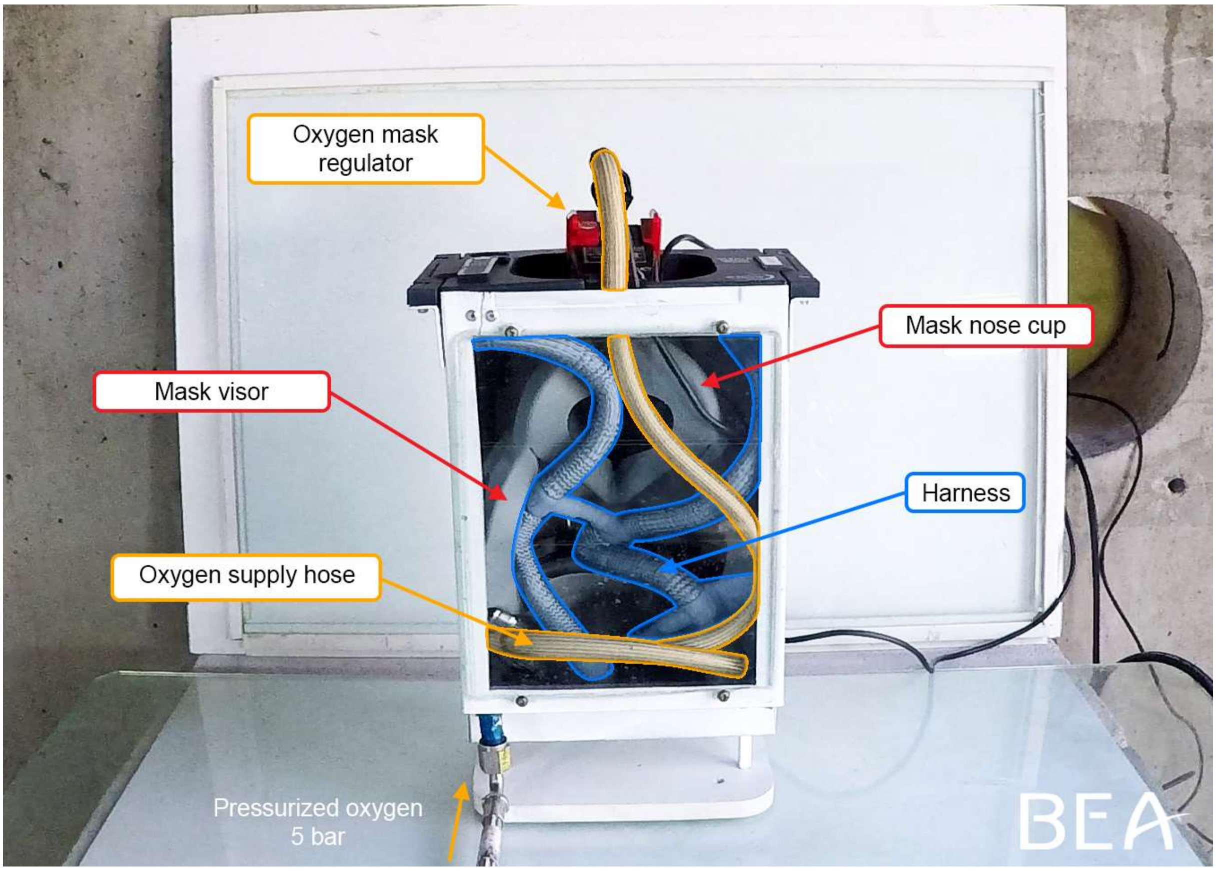


Figure 30: mask storage box with glass panel (source: BEA)

Each test was subdivided into several sequences:

- handling of cigarette near the box;
- handling of cigarette at the box opening, level with the mask regulator;
- introduction of ash into the mask storage box;
- introduction of a whole cigarette into the box.

These tests were carried out three times with different oxygen concentrations in the box.

	Duration of oxygen enrichment
Cigarette_01	15 s via the system solenoid valve with the mask knob in the *EMERGENCY* position
Cigarette_02	20 s by pressing the *EMERGENCY* knob
Cigarette_03	20 s by pressing the *EMERGENCY* knob
Cigarette_04	7 s by pressing the *EMERGENCY* knob

Sequences 1 & 2: Handling of cigarette near the box

When the glowing cigarette was handled close to the box, no variation in the intensity of combustion was observed. Each time, the cigarette burned at the same rate as in the open air. As oxygen is heavier than air, although the box was enriched with oxygen, outside the box or in the direct vicinity of the regulator, the composition of the atmosphere remained close to the normal composition of ambient air.

Sequences 3: Introduction of ash
No ignition occurred when ash was introduced into the box. The mass of the ash was probably too small to retain the heat needed to produce a flame. The ash burnt instantly.

Sequences 4: Introduction of a cigarette
When a glowing cigarette was placed in the box, there was a sudden increase in its rate of burning. Combustion was more intense and whiter. Flames were visible and black smoke was produced.

During the first test (Cigarette_01), the cigarette landed on the mask's harness and perforated it. The fire did not spread to other parts of the mask and extinguished.

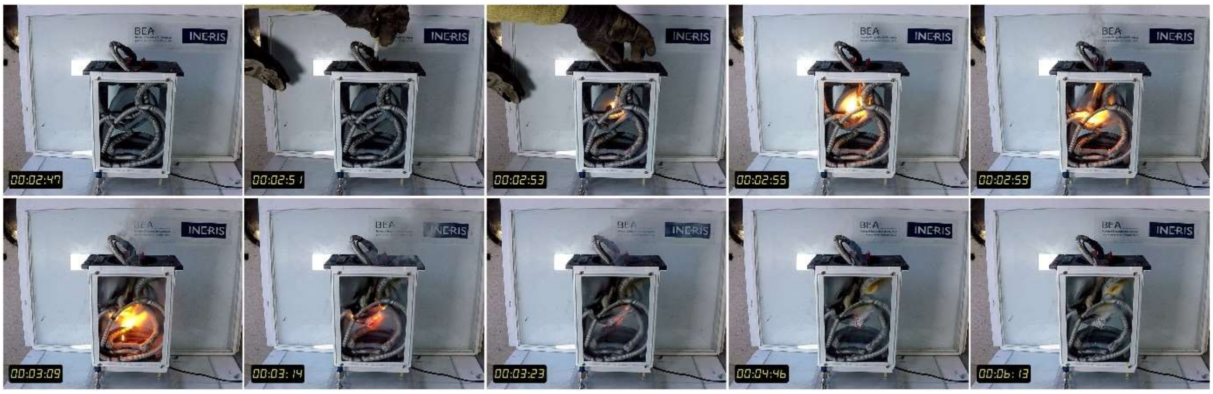


Figure 31: cigarette_01 test - video sequence (source: BEA)

During the second test (cigarette_02), the cigarette landed on the silicone envelope of the oxygen mask nose cup and began to consume this part of the mask. When the oxygen contained in the box was consumed, the intensity of the fire decreased and the fire went out.

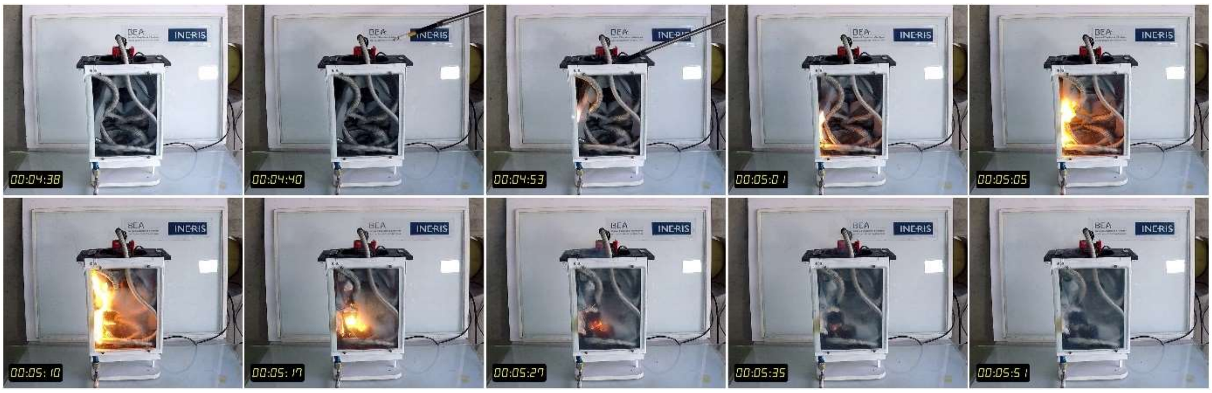


Figure 32: cigarette_02 test - video sequence (source: BEA)

In the next two tests, the cigarette was placed in contact with the mask's oxygen supply hose. The flames damaged the casing of the hose and after a few seconds, its core (silicone tube) was pierced; a leak at a pressure of 5 bar was caused and the fire rapidly developed in the box, producing flames which escaped from the mask storage box. Cutting off the oxygen supply extinguished the fire after a few seconds.

Audio analysis

Cigarette_03 test: crackling noises for 28 s were audible on the recording, corresponding to the combustion of the hose casing. The subsequent piercing of the hose produced a broadband noise. 1 s later, the mask ignited, causing a sound runaway. The mask microphone stopped working 6 s after the mask ignited.

Cigarette_04 test: crackling noises for 22 s were audible, corresponding to the combustion of the hose casing. The subsequent piercing of the hose produced a broadband noise. The mask ignited 0.5 s later, causing a sound runaway. The oxygen supply was cut off before the mask microphone was damaged.

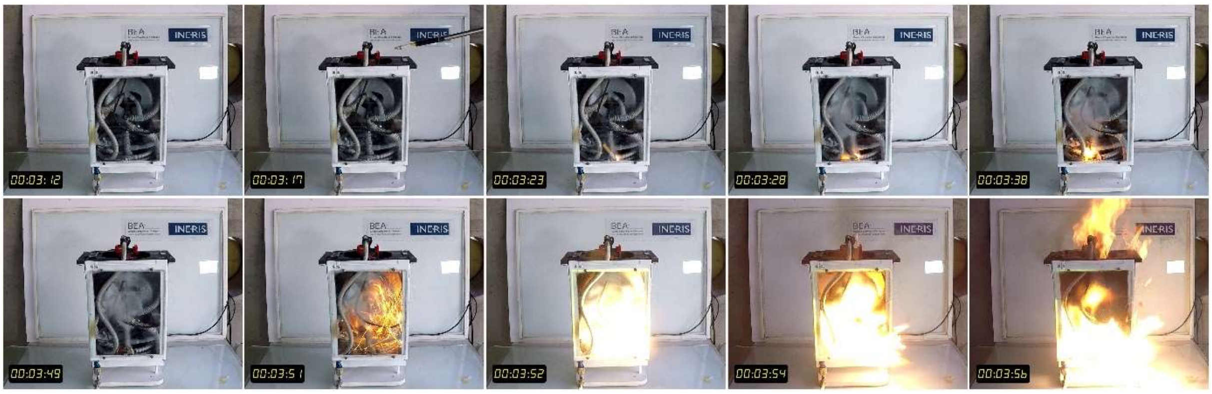


Figure 33: cigarette_03 test - video sequence (source: BEA)

Figure 34: cigarette_04 test - video sequence (source: BEA)

CONCLUSION
In the tests carried out, the handling of a cigarette in the immediate vicinity of an oxygen mask storage box, even if the box had been enriched with oxygen, did not lead to any variation in the combustion of the cigarette and did not cause a fire. The introduction of hot ashes into the storage box did not start a fire. In each test, placing a cigarette in a mask storage box that had been enriched with oxygen accelerated its burning rate and produced a more intense flame. When the cigarette came into contact with an oxygen supply hose, the fire attacked the hose, pierced the internal silicone tube and created an oxygen leak under pressure. The leak intensified the fire, allowing it to spread rapidly.

5.2.2 Internal ignition mechanisms

The certification indicates that the system must be intrinsically safe. In particular, the system's design must be such that a single failure of one of its components does not lead to an uncontrolled fire in the aeroplane and that in all cases, such a fire is extremely improbable.

The risk analysis of the oxygen system must look at the failures of the various components, the properties of the materials and the internal ignition mechanisms. If an internal ignition mechanism exists, the associated fire kindling chain must be analysed.

5.2.2.1 A heat source causing ignition inside the device

The aim was to describe the sequence that would arise from internal damage from an acoustic point of view (appearance of transient noise phenomena, noises, whooshing sounds, etc.), to determine the level of damage produced on the individual oxygen equipment (mask storage box and mask) placed under a pressure of 5 bar, and to specify the chronology of this damage (propagation time).

To artificially cause internal damage to the oxygen distribution system - and more specifically to the oxygen mask hose - a spark-trigger device[33] was introduced into the hose.

Figure 35: spark production device (source: BEA)

[33] A two-wire connection that provides a continuous low-voltage supply to a filament; the filament becomes incandescent when it is connected via a pushbutton to a voltage source.

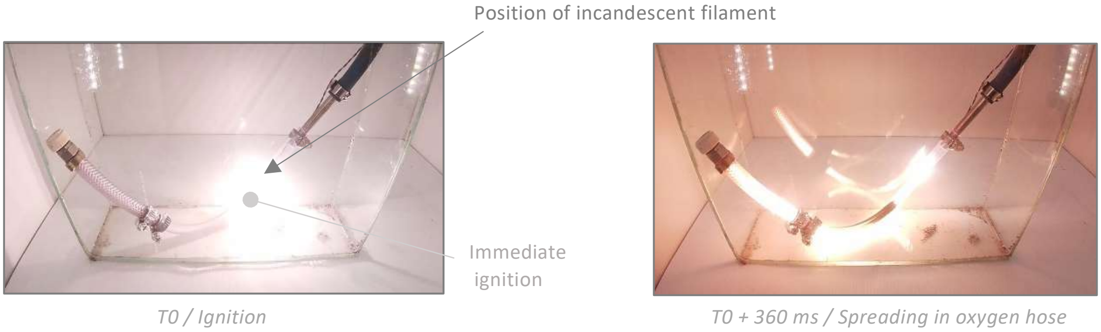


Figure 36: fire in oxygen flow (source: BEA)

An initial test carried out in a transparent tube confirmed that ignition at the point where the spark is created was immediate.

Three tests were carried out using a mask storage box with a front glass panel, with the spark-production device inserted halfway along the mask hose.

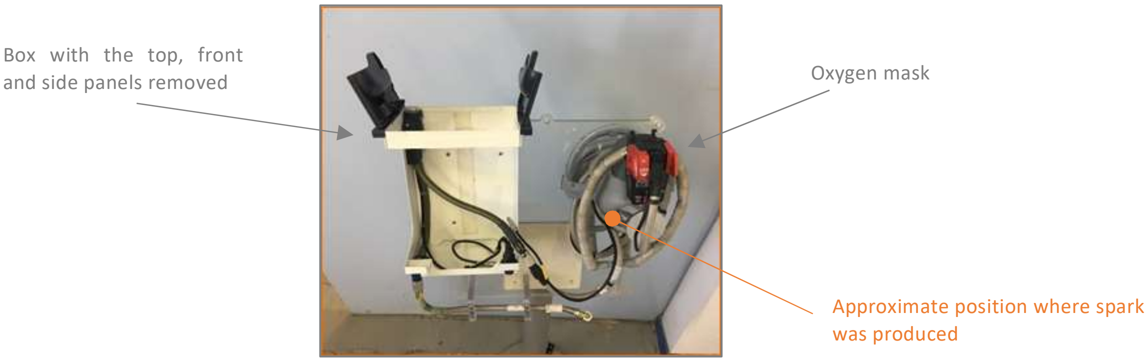


Figure 37: insertion of device in hose of oxygen mask (source: BEA)

Note: During these tests, the combustible material represented by the visor support (silicone) and the visor (polycarbonate) were removed.

Tests: the volume of the mask storage box was first enriched with oxygen by pressing the *EMERGENCY* knob on the oxygen mask regulator for a few seconds.

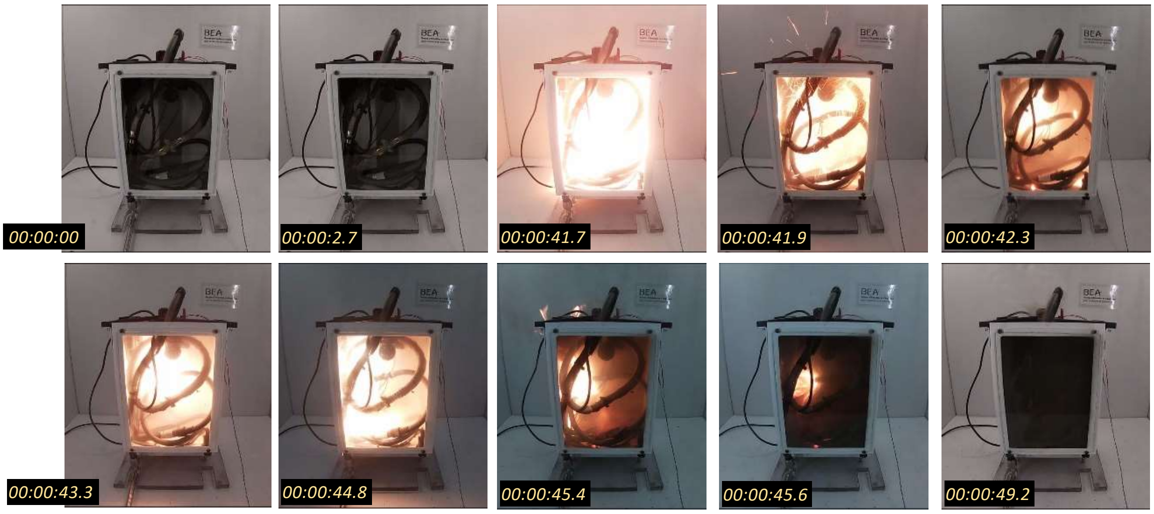


Figure 38: internal damage to mask oxygen hose (source: BEA)

During the first test, immediate damage occurred inside the hose (appearance of a moving glow in the tube); the hose was punctured and the fire spread to the surrounding area 42 s after the spark was created.

In the second test, no immediate internal damage was detected; the hose was punctured and the fire spread to the surrounding area 30 s after the spark was created.

The last test did not produce any ignition of the box[34]. The puncture occurred 18 s after the spark was created.

The production of a spark in the oxygen supply hose of the mask sometimes created a puncture in the hose after 20 to 40 s. In some cases, the puncture was accompanied by a fire that spread rapidly to the surrounding area when the flow of oxygen was maintained.

CONCLUSION

In the three tests, the creation of a spark in one of the mask's oxygen supply hoses produced instant ignition.

The ignition did not have a detonating effect. It led to the hose being punctured after 20 to 40 s. In some cases, the puncture was accompanied by a fire that spread rapidly to the surrounding materials when the flow of oxygen was maintained.

5.2.2.2 Metal particle impacts in the oxygen system

Particle impacts are one of the internal ignition mechanisms to be considered in the hazard analyses. This hazard relates in particular to particles that could be introduced into the system during maintenance operations.

[34] The puncture occurred two seconds after the oxygen supply to the mask storage box and mask was cut off.

During the maintenance of oxygen systems on commercial air transport aeroplanes, particular care is taken not to contaminate the oxygen distribution system.

However, it is possible for particles to be accidentally introduced into the lines carrying the oxygen. For example, operations to replace one or more sub-assemblies of the individual oxygen equipment (storage box, mask, etc.) may produce metal residues during connection operations when the components are screwed together (e.g. partial breakage of screw threads, metal seals or unions).

These metal particles could present a risk of ignition of the oxygen system when there is a pressurised gas flow. When the gas is set in motion, the particle accidentally introduced advances through the system, accelerating. The various changes in direction of the hoses or rigid pipes can potentially cause the particle to collide with other metal components (filter, elbow, etc.) that make up the oxygen distribution system. This impact can be accompanied by a high, localised rise in temperature (linked to the transfer of kinetic energy) which, in an oxygen-rich environment, can lead to the start of a fire. This is referred to as “particle impact ignition”.

According to the literature[35], the scenario of a fire starting as a result of the impact of a metal particle in the oxygen system of a commercial aircraft is possible. The necessary criteria for this outbreak are:

- particles circulating in a flow of oxygen;
- gases travelling at more than 30 m/s; and
- an impact plane between 45° and 90° to the path of the particle.

Tests were carried out in a laboratory environment to try and reproduce this phenomenon. A test bench was set up to project particles at high speed against a component to be tested.

[35] NASA doc

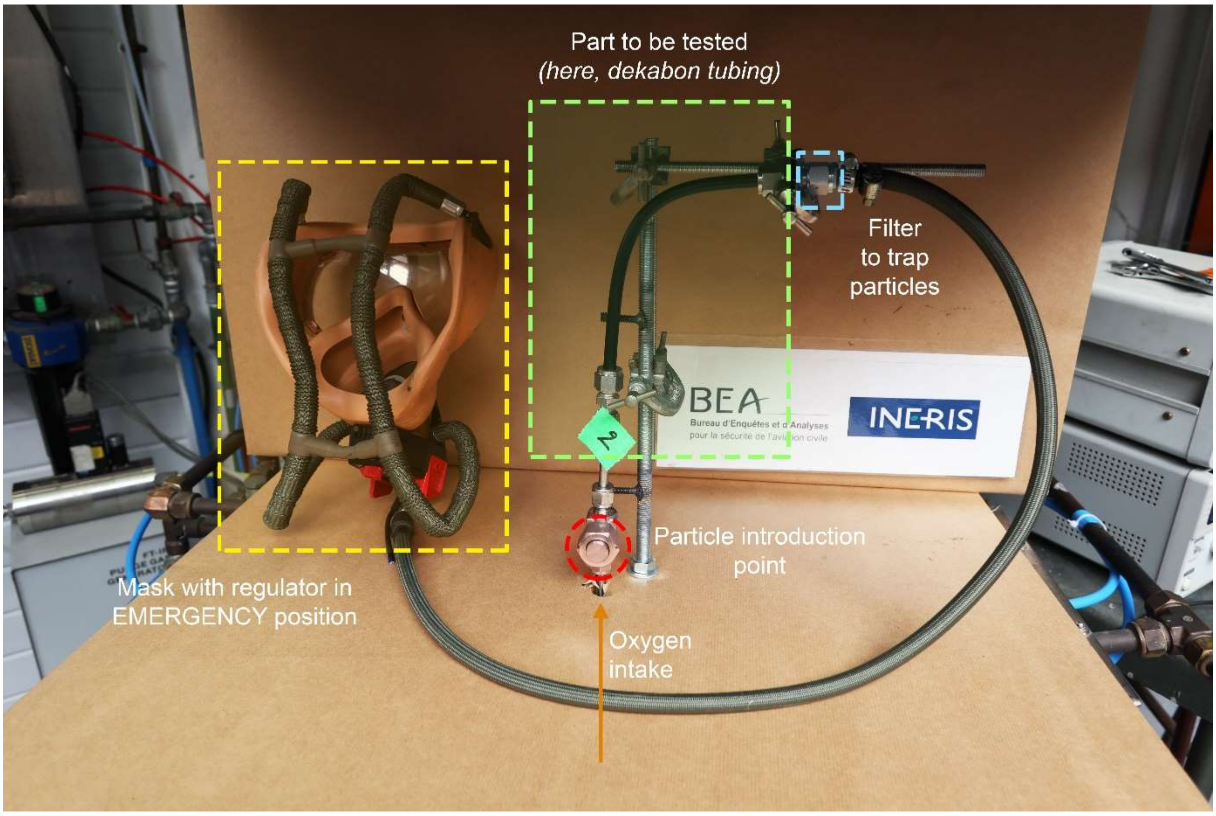


Figure 39: test set-up (source: BEA)

Description of installation: the test system was supplied with oxygen at a pressure of 5 bar. A mask positioned at the end of the line with the knob in the EMERGENCY position was used to create a pressure drop consistent with that in an aircraft oxygen system.

The oxygen passed through a filter on which metal particles had been deposited. The flow of oxygen and particles travelled through the system to the component to be tested. The particles were then collected on a filter to avoid saturating the oxygen mask placed at the end of the line.

Each part of the system was tested with particles of different sizes from different materials. The aim was to identify the "part/particle" pairing most likely to create the sought for particle impact ignition phenomenon.

A total of five parts of the oxygen system, located in the mask storage box or regulator, were considered:

	Parts to be tested
1	90° inlet elbow
2	Dekabon tubing
3	Box valve piston - in this part of the system, the oxygen flow takes a 180° bend
4	135° inlet union of mask regulator
5	Oxygen mask inlet filter

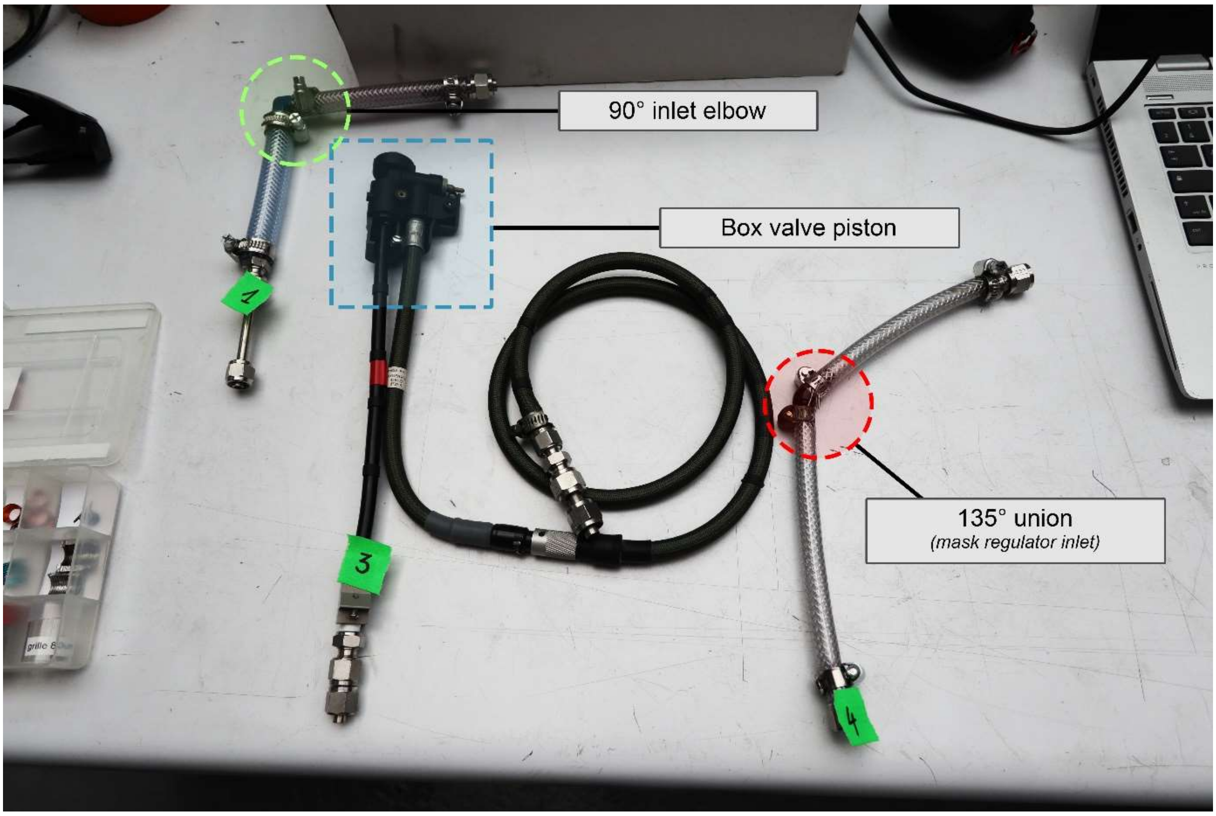


Figure 40: mask parts tested during particle tests (source: BEA)

The particles were created from parts of the oxygen system:

	Particles
A	Aluminium from the inlet elbow of the mask storage box
B	Copper from crush seals in the distribution circuit
C	Aluminium from Dekabon tubing
D	Stainless steel from oxygen supply hoses

Particles of two sizes were produced from each material:

- around 300 µm in size;
- around one millimetre in size.

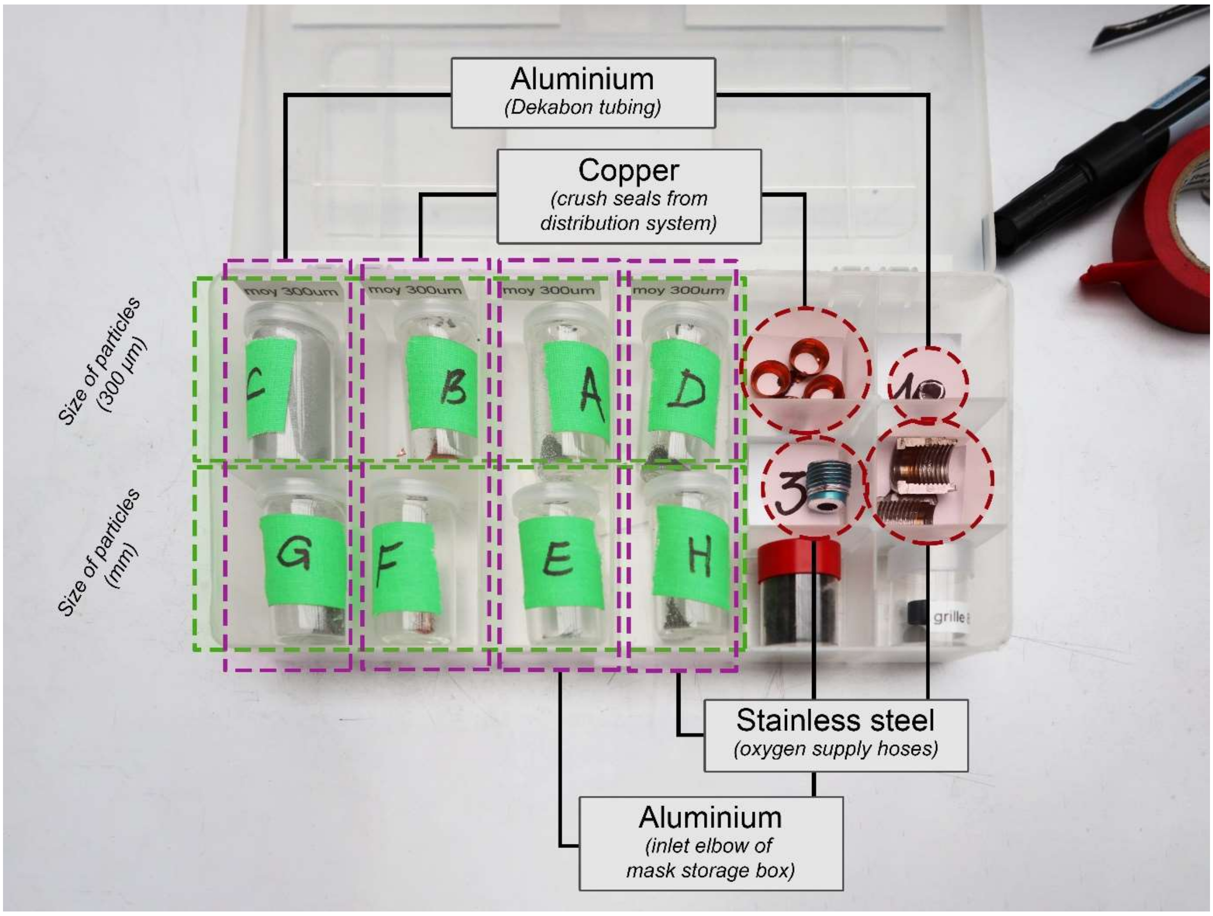


Figure 41: particles used (source: BEA)

For each test, several oxygen bursts at an average pressure of 5 bar and a constant flow rate of 200 l/min were sent through the system (this corresponded to an estimated gas travel speed of more than 50 m/s). A thermal camera directed towards the part to be tested, monitored the potential rise in local temperature at the time of the “particle impact ignition”.

The tests for each "part/particle" pair were carried out between three and five times with different quantities of particles.

A total of 76 tests were carried out. No particle impact ignition or increase in temperature were observed during the tests.

Note: Due to the architecture of the test bench, some particles may have been trapped in the filter and not set in motion at each pressurisation (three to five successive pressurisations per "part/particle" pair). The chances of particles colliding with a part were therefore lower than the number of tests.

The particle impact ignition phenomenon is random in nature. New tests could be carried out by modifying the test conditions to increase the quantity of the sample and the probability of reproducing a particle impact ignition.

Figure 42: overall view of particle test equipment (source: BEA)

CONCLUSION

The "particle impact ignition" phenomenon described in the literature was not reproduced in the test conditions adopted.

5.2.2.3 Ignition due to electrostatic discharge

The discharge of electrostatic charges accumulated by friction or flow can in some cases release sufficient energy to ignite materials, particularly when the environment is rich in oxygen. This can happen when materials used in the systems exhibit differences in electrical potential.

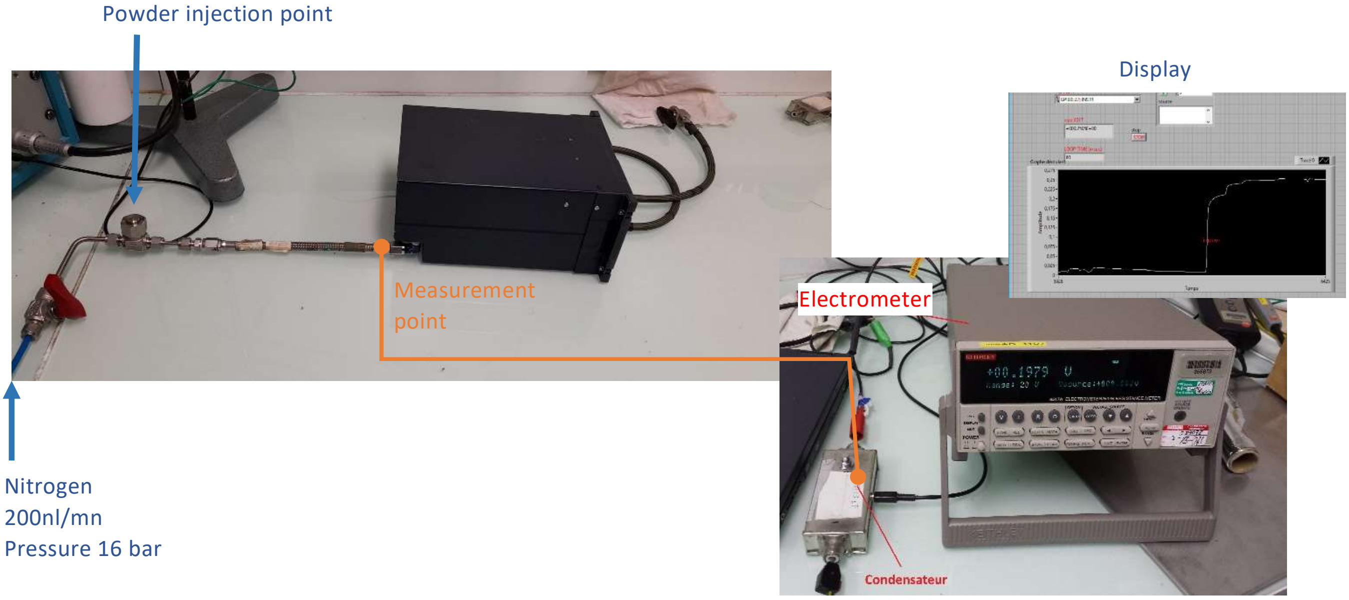
The aim was to determine whether the electrostatic charges generated by the dynamics of the passage of oxygen, combined with the movement of particles in the system, could create an arc likely to generate the start of a fire.

Electrostatic charge measurements were carried out at various points on a complete oxygen system (supply hose, storage box, mask) in which nitrogen at 6 bar and a flow rate of 200 l/min was travelling. Two types of powder were used for these tests:

- conductive metal powder (400 µm aluminium);
- insulating polystyrene powder (600 µm).

For these tests, the mask was stored in its box, where the accumulation of charges was thought be the greatest. Three measurements were carried out:

- at the threaded connection at the storage box inlet;
- at the inlet hose of the mask regulator;
- at the filter in the mask regulator.



*Note: the charge is determined by Q=C*U with Q in nC, C in Farad, and U in Volt.*

Figure 43: measurement method of electrostatic charge (in compliance with technical specification CEI/TS 60079-32-1) (source: INERIS)

Measurement principle:
The electric potential (instantaneous voltage measurement) taken at the inlet union of the mask storage box was accumulated over a defined period by a capacitor whose average charge is measured by an electrometer. This charge, expressed in nanoCoulomb (nC), expresses the level of electrostatic charge accumulated at the measurement point.

The charges measured in nC during these tests were as follows:

	Aluminium	Polystyrene
Box inlet union	2 nC	1 nC
Regulator inlet hose	16 nC	2 nC
Mask filter	22 nC	4 nC

These values were too low to create a spark capable of igniting a part in the oxygen system. By way of comparison, in an explosive atmosphere, electrostatic charges present a risk at values above 200 nC.

The electrostatic fields were also measured on a mask stored in a box containing polyester fabric lint. It is not uncommon to find an accumulation of dust in the bottom of mask storage boxes after several weeks or months in service. The measurements were taken after nitrogen had been injected into the system.

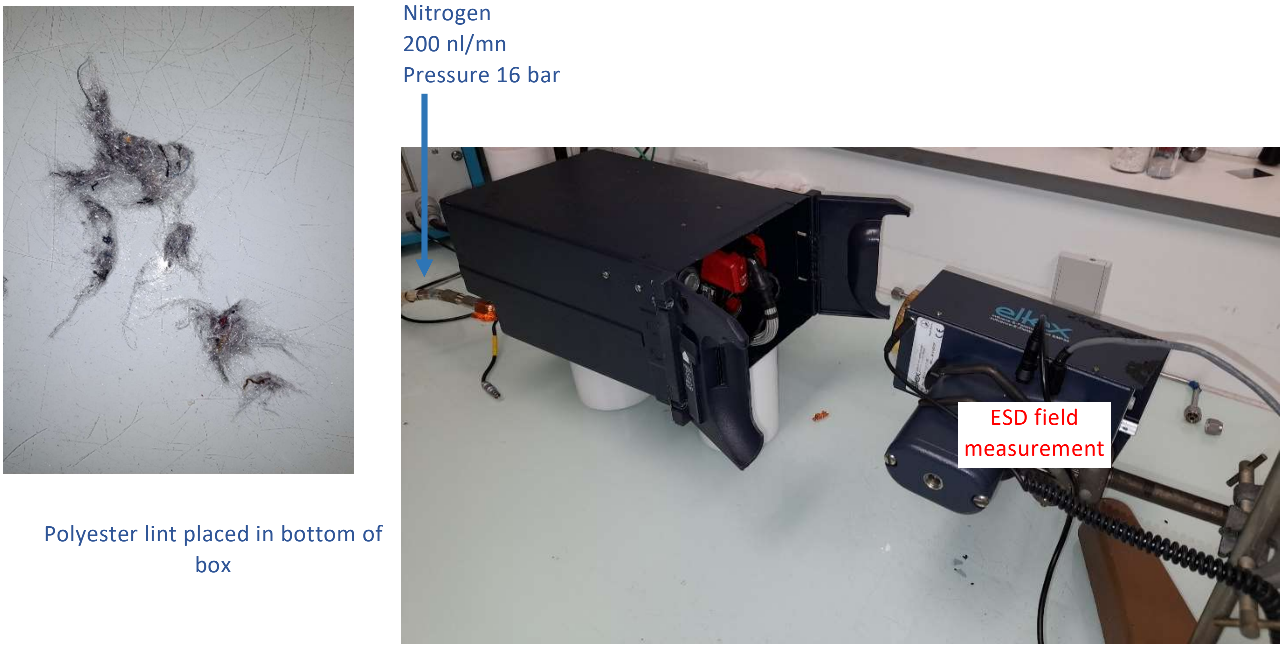


Figure 44: measurement of electrostatic fields created on accumulated synthetic debris at bottom of storage box (source: INERIS)

The maximum voltage observed was 255 V; this voltage was too low to generate an electrostatic charge likely to produce sparks capable of igniting dust or metal particles. In an explosive environment, the formation of dangerous sparks is considered for a value greater than 2 kV.

CONCLUSION

The measurements carried out on the oxygen system of a commercial air transport aeroplane seemed to indicate that the accumulated electrostatic charges were too low to create sparks capable of igniting elements of the system itself or organic or synthetic debris present in the storage box.

5.2.3 Ignition of substances in an oxygen-enriched environment

5.2.3.1 Oxidation of grease

The scientific article entitled "*Fire and Explosion Hazards Due to Medical Oxygen Handling During Coronavirus Pandemic*" describes in detail the chemical oxidation reactions likely to produce temperatures reaching the spontaneous combustion temperatures of certain materials. This document refers to the known risk associated with the use of greases in an oxygen-enriched environment.

According to a summary provided by INERIS, in the scope of the study:

It is generally accepted that grease can react with oxygen by oxidation (decomposition of the grease molecules) leading to the production of radicals (peroxides), an increase in temperature and then possibly combustion if sufficient energy is supplied (heating by friction or creation of an electrostatic charge, for example).

Normally, this oxidation does not produce enough heat to lead to combustion, except in special conditions such as:

- large exchange surfaces between grease and oxygen;
- poor air circulation (conducive to heat build-up);
- adiabatic compression following rapid injection of pressurised oxygen into a non-pressurised system. However, a pressure of 5 bar seems too low to ensure a sufficient production of energy.

All materials ignite in the presence of oxygen at temperatures lower than their ignition temperature in ambient air.

When analysing events that had occurred on cockpit oxygen systems, the possibility that the start of the fire was related to the presence of grease could not immediately be ruled out, particularly if the grease traces in question were hydrocarbon-based. However, it is more difficult, if not impossible, for a fire to start if the greases used are "non-reactive" (e.g. fluorinated greases). The aging condition of a grease must also be taken into account, as it increases the risk.

This risk was not the subject of any specific experiments in the scope of this "Oxygen fire" study. The only test carried out consisted of the deliberate introduction of grease during a propagation test (see paragraph 5.4) into an oxygen mask storage box union; no fire was triggered when oxygen was admitted and circulated in the system under a pressure of 5 bar.

This test illustrated that the spontaneous combustion of grease in an oxygen-rich environment is not systematic and that it occurs under specific conditions (type of grease, oxygen pressure, flow rate, etc.).

The variables to be controlled, such as trigger conditions, type of grease and oxygen pressure, would require the definition of a dedicated protocol and multiple tests, which could not be carried out as part of the study.

The main supplier of oxygen systems[36] for commercial aviation, and the reference organization[37] for the risk analysis of oxygen and hydrogen systems, have produced a summary which is presented in the appendix, Grease and hydrocarbon ignition. The analysis indicates that the mere presence of grease exposed to a pressure of less than 10 bar - which is much higher than the operating pressure of a mask storage box and associated mask - cannot generate a fire.

[36] SAFRAN Oxygen Systems
[37] WHA International Inc / https://wha-international.com/about/

CONCLUSION

Greases are hydrocarbons that react with oxygen in the air to form peroxides. This oxidation reaction releases heat. Heat can be sufficient to undergo grease combustion.

The risk represented by the presence of grease in an oxygen-rich environment is commonly accepted and taken into account in procedures. However, the conditions under which spontaneous combustion occurs are poorly documented in the aeronautical field.

The only test carried out highlighted the fact that the ignition of grease in an oxygen-enriched environment is not systematic.

5.2.3.2 Ignition of dust

Mask storage boxes may contain dust that has accumulated over time.

The aim of the tests was to determine whether the addition of heat could cause the dust to ignite, and whether this would be sufficient to damage the oxygen system.

To reproduce the accidental ignition of dust, a device producing an electric arc[38] was introduced into an oxygen-saturated enclosure.

Figure 45: spark produced by the piezoelectric system (source: BEA)

A first test was carried out on domestic dust. Several attempts were made to ignite the dust by producing a spark in the middle of the pile of dust. No incipient ignition was observed.

[38] The head of a friction piezoelectric igniter was remotely controlled by a two-wire line.

Figure 46: domestic dust (source: BEA)

A second test was carried out on dust taken from the bottom of oxygen mask storage boxes in three aircraft. Several attempts were made to ignite the dust by producing a spark in the middle of the pile of dust. No incipient ignition was observed.

Figure 47: aeroplane dust (source: BEA)

CONCLUSION

The production of a spark (electric arc) in a pile of dust placed in an environment previously saturated in oxygen did not, under our test conditions, produce immediate ignition.

5.3 Extinguishing a fire in the presence of an oxygen leak: use of halon extinguishers

The cockpits of commercial air transport aeroplanes are equipped with portable halon fire extinguishers, also known as halogenated hydrocarbon extinguishers.

These extinguishers contain halon 1211 expelled by the pressure of an auxiliary gas (nitrogen). It acts by inhibiting the combustion reaction by combining with the oxygen in the atmosphere, thus depriving the combustion of comburant.

The action of a halon extinguisher is faster than that of a carbon dioxide extinguisher and requires less product. This makes it a smaller and lighter extinguisher.

Halon presents little risk when cold. On the other hand, in the presence of high temperatures, which can occur in prolonged and extensive fires, its pyrolysis products can be highly toxic and corrosive. Halon has no cooling effect, unlike carbon dioxide.

Halon extinguishers should be used at a distance of about 1 m from the flames, attacking the fire at its base as soon as flames are visible. The maximum angle of use for this type of extinguisher is 45° in order to keep the dip tube in the liquid extinguishing agent and not to expel just the auxiliary propellant gas.

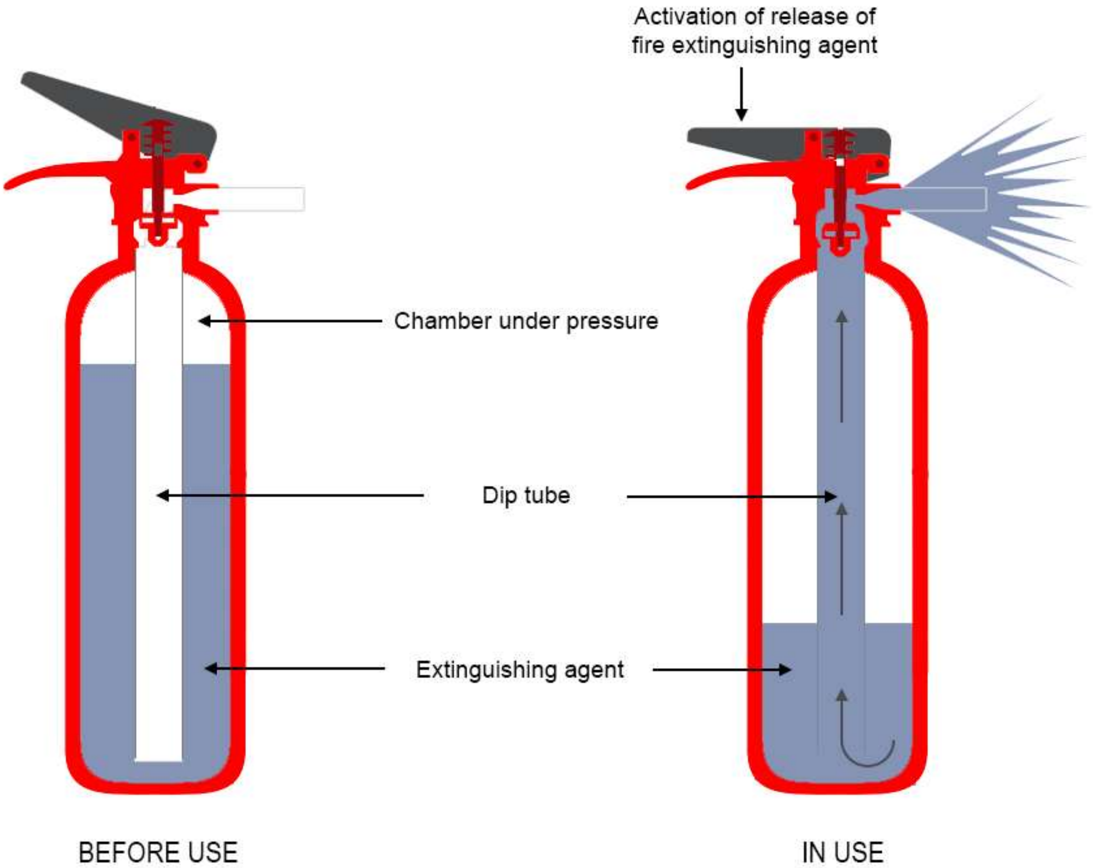


Figure 48: halon extinguisher operating principle (source: *L'avionnaire*)

The study looked at the effectiveness of the fire extinguishers available in the cockpit for extinguishing a fire in the presence of an oxygen leak.

Three tests using halon extinguishers were carried out on a fire contained in a metal firebox into which oxygen was introduced via a hose located at the bottom of the box to simulate an oxygen leak. A flame was supplied with fuel in the centre of the firebox (a Hessian wick placed in an oil bath).

The model of extinguisher used for these tests was the Air Total 74-20.

Extinguisher_01	Fire extinguisher used on non-oxygen enriched firebox
Extinguisher_02	Fire extinguisher used on firebox with oxygen leak
Extinguisher_03	Fire extinguisher used on firebox with oxygen leak

The measurements showed that an extinguisher was completely discharged in 14 to 18 s.

A first test was carried out without the addition of oxygen (Extinguisher_01 test); the flames disappeared as soon as the extinguisher was activated. The fire did not restart again. There was no change in visibility in the room.

Figure 49: extinguisher_01 test - video sequence (source: BEA)

During the fire extinguisher_02 test, the fire was enriched with oxygen. The halon extinguisher was unable to extinguish the fire. No effect on the flames was observed. On activation of the extinguisher, thick smoke appeared, significantly reducing visibility.

Figure 50: extinguisher_02 test - video sequence (source: BEA)

The protocol followed for the fire extinguisher_03 test was identical to the previous one, except that there was practically no oil in the oil bath. The flames were extinguished as soon as the extinguisher was activated[39]. The oxygen leak was present throughout the test. There was a detonation 12 s after the extinguisher had been emptied, and the flames reappeared.

Figure 51: extinguisher_03 test - video sequence (source: BEA)

The tests showed that the use of a halon fire extinguisher is not suitable for extinguishing an oxygen-enriched fire.

Halon acts on oxygen to inhibit the combustion reaction. The continuous oxygen leak prevented the extinguishing agent from overcoming the accumulation of oxygen in the environment. Thus, either the fire was not extinguished because there was enough oxygen to support combustion, or the fire was extinguished but the sustained supply of oxygen and the high combustion temperatures reached allowed the fire to start again. As halon has no cooling effect on the elements, the residual embers recreated flames in the presence of oxygen.

CONCLUSION

During the tests, a fire fuelled by an oxygen leak could not be extinguished using halon extinguishers. This result is consistent with the chemical mechanism by which halon gas acts on a fire. The halon acted on the oxygen, but the leak continued to supply oxygen to the fire.

During the three tests, the presence of an unpleasant odour, and acidic, irritating emanations was noted. The video and sound recording equipment was damaged by the acid vapours released when the fire extinguishers were used (particularly during the "Extinguisher_02 test").

The identification of the gases produced during each of the three tests[40] gave rise to the following list and level of gases resulting from the combustion and degradation of halon:

- carbon gases: COF2 - carbonyl fluoride and CF4 - carbon tetrachloride;
- acids: HF - hydrogen fluoride, HCl - hydrogen chloride, and HBr - hydrogen bromide;
- halon (extinguishing agent): halon.

The tables in the appendix, Halon gas give details of the gas levels produced during three separate tests, which were carried out under different conditions:

- the first test consisted of using a halon fire extinguisher to put out a fire without oxygen enrichment (example of the "*Extinguisher_01 test*") and without ventilation;
- the second consisted of attempting to put out an oxygen-enriched fire (example of the "*Extinguisher_02 test*") with ventilation of the test space[41];
- the last test involved extinguishing a fire enriched with oxygen but rapidly deprived of fuel (example of the "*extinguisher_03 test*"), again with ventilation of the test area.

[40] Ambient air samples were taken from the test chamber suction system.

[41] The air extraction volume was much higher (5000 m3/h) than that of an airliner cockpit ventilation system (between 0.13 and 0.15 m3/s).

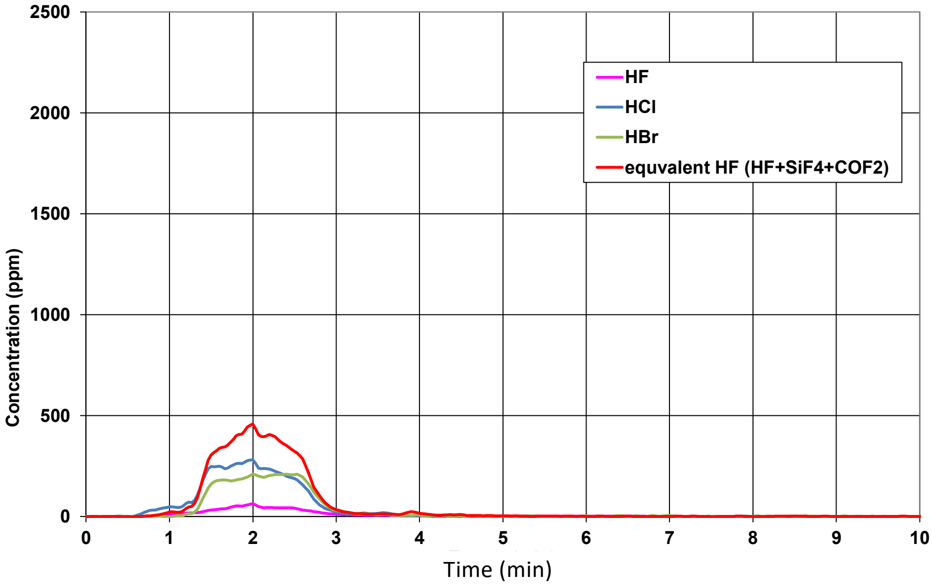


Figure 52: example of a table giving acid gas measurements (source: INERIS report)

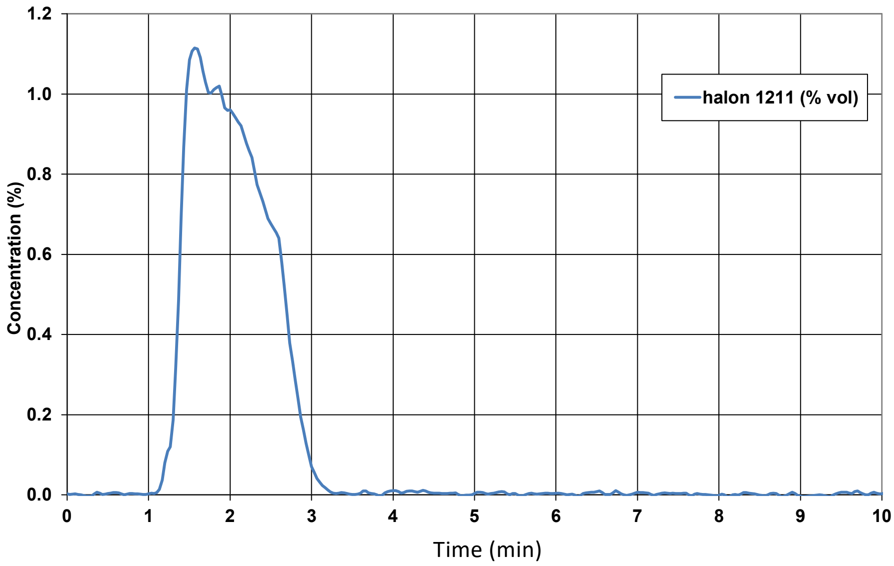


Figure 53: example of a table giving halon measurements (source: INERIS report)

All the measurements were compared with the gas toxicity thresholds for a 10-minute exposure of personnel (see appendix, Halon gas for details).

It appeared that during the three tests, the COF2 concentration exceeded the irreversible effect threshold. During the test carried out without ventilation, the concentration of HF and HCl largely exceeded the irreversible effect threshold. Lastly, INERIS indicated that during the "Extinguisher test_02", exposure to the cumulative gases generated reached the irreversible effect threshold, and probably the first lethal effects (see concept of *toxic dose* described in the appendix, Halon gas).

The INRS toxicological data sheet for Bromochlorodifluoromethane (CFC2ClBr, halon 1211) states: When using this product in a portable fire extinguisher, take care not to expose people to pyrolysis products. HF, HCl and HBr acid gases are toxic and corrosive pyrolysis products.

The acid gases identified during the tests (HF, HCl and HBr) correspond to these pyrolysis products. They are toxic and corrosive.

CONCLUSION

During the tests, using a halon fire extinguisher on an oxygen fire produced opaque smoke that rapidly invaded the environment. Visibility became almost zero. The pyrolysis of the halon created acid gases in quantities that were harmful to people in the vicinity of where the fire was being put out.

5.4 Propagation (and extinction) of a fire in the presence of an oxygen leak

Three tests involved the propagation of a fire started in an oxygen mask storage box.

The tests were carried out using structural elements (lateral storage compartments) taken from an A318 and an A319 that were being torn down. A mask storage box and the associated oxygen mask were placed in this lateral compartment. The fire was started in the storage box using a remote-controlled flame. A fire extinguisher, operable from the outside for safety reasons, was placed on a fixed support and aimed at the storage box.

The three tests carried out differed in terms of the means used to create the oxygen leak and the subsequent fire extinguishing sequence. The table below shows the different configurations adopted.

	Propagation_01	Propagation_02	Propagation_03
Test Environment	10 m3 chamber: Lateral compartment + storage box with oxygen mask		
Start of fire	Caused by a flame in the storage box		
Start of oxygen leak	Mask set to EMERGENCY (controlled by a solenoid valve)	By propagation of fire	
Activation of fire extinguisher	No	Yes	After oxygen cut off*

*The tests carried out with the fire box in the presence of oxygen showed the relative ineffectiveness of halon on an oxygen-rich fire. The propagation_03 test was designed to incorporate this result by adding the cutting off of the oxygen prior to using the fire extinguisher.

Propagation_01 test:

The fire was started by a flame created in the storage box (at 00:48 in the video[42]). The oxygen leak was started from outside the test chamber via the solenoid valve in the oxygen supply system, after the fire had had time to develop to a small extent inside the box[43].

High flames appeared rapidly; the fire was intense. In the seconds that followed, the fire seemed to diminish until it disappeared. The sound of leaking oxygen seemed to die down. Only black smoke remained visible, slightly obscuring the room. After several dozen seconds, flames were again visible in the mask storage box. The sound of oxygen leaking stopped for half a second, then a detonation was heard (at 01:39), accompanied by sparks and a reddish glow in the environment of the lateral storage compartment. More and more black smoke escaped.

The fire was hidden and contained in the lateral storage compartment; it was barely visible in the shots. Its intensity seemed to increase progressively until flames escaped again through the oxygen mask storage box where the fire was initially started (at 01:56). As soon as the flames emerged, they spread to the rest of the lateral compartment, in particular to the second oxygen mask. The fire intensified. The room was filled with increasingly opaque smoke. Incandescent material was projected at 02:28, then the lateral compartment cover closed over the mask storage boxes. Flames next escaped from around the edges of the storage box.

The oxygen supply was cut off and the fire extinguished using water-spray fire extinguishers.

Audio elements: when the mask hose was pierced 18 s after the fire broke out, a broadband noise (leaking noise) was heard, immediately followed by a sound runaway. The leaking noise stopped 0.5 s - without any action by the test operators - 50 s after the mask hose was pierced. The interruption was followed by a detonation, the resumption of the leak and the enrichment of the fire.

[42] The timing indicated corresponds to that of the raw file of the camera recording.
[43] The mask regulator knob was set to *EMERGENCY* to obtain a continuous flow of oxygen.

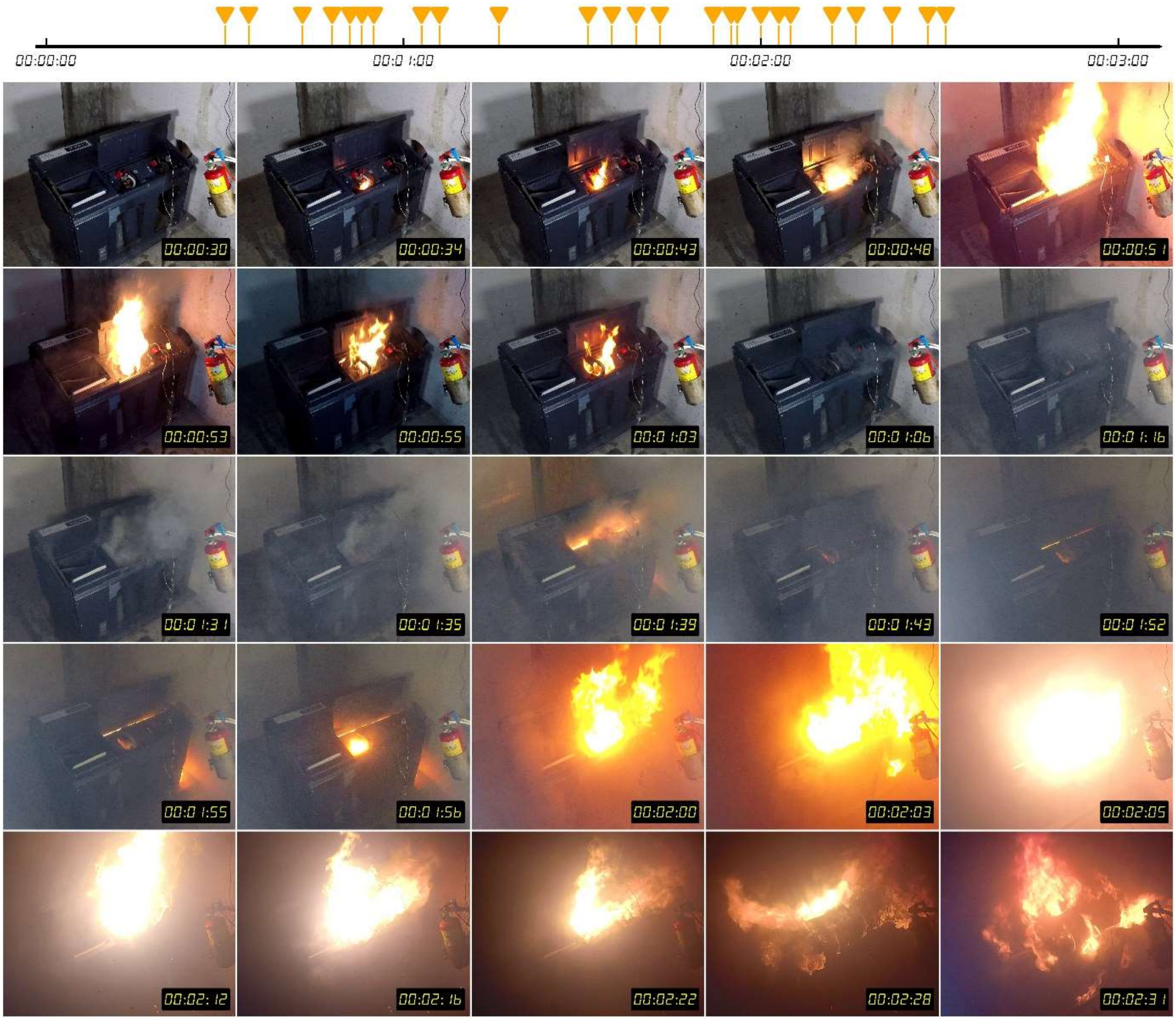


Figure 54: Propagation_01 test - video sequence (source: BEA)

Propagation_02 test:

The fire was started by a flame created in the mask storage box (at 10:52 on the video[44]). The flame was positioned close to the mask's oxygen supply hose to damage it and create an oxygen leak (at 10:58). The mask storage box had been previously enriched with oxygen to encourage the fire to start.

After the fire was established in the presence of the oxygen leak, the fire extinguisher was activated (at 11:22). The flames were quickly smothered and thick, opaque smoke filled the room. About 20 s after the fire extinguisher was activated, despite the smoke, glowing flames were visible in the oxygen mask storage box. The fire continued to intensify in the following seconds until the oxygen supply to the test chamber was deliberately cut off. The fire was extinguished using water-spray fire extinguishers.

Note: this test was carried out in February 2023 in an uninsulated room that had not been heated beforehand.

[44] The timing indicated corresponds to that of the raw file of the camera recording.

Audio elements: the piercing of the mask hose 13 s after the reactivation of the fire was preceded by crackling noises (picked up by the microphone on the oxygen mask). The piercing of the hose produced a broadband noise (leaking noise). The mask microphone stopped working 5 s after the hose of the oxygen mask was pierced.

The fire that followed the piercing of the hose spread rapidly to the surrounding components. No sound runaway or interruption in the leaking sound was observed.

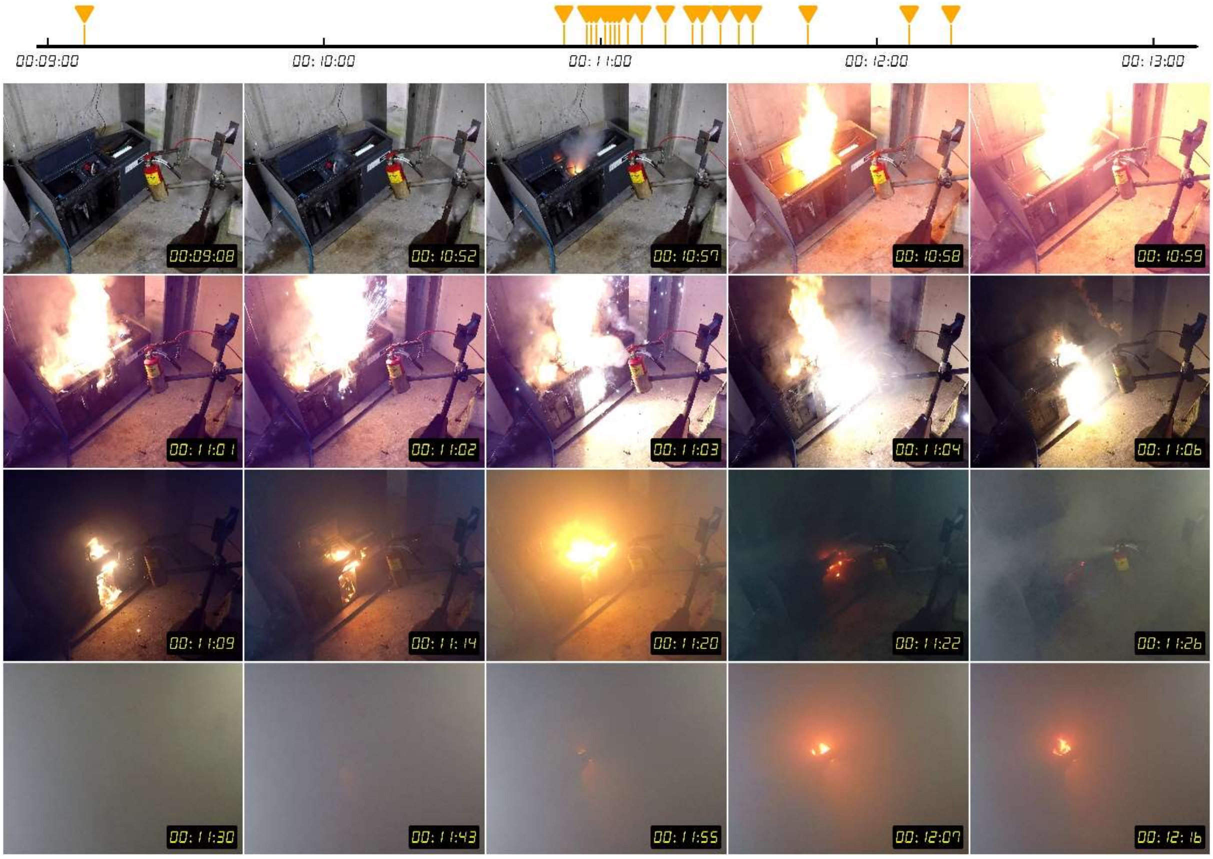


Figure 55: Propagation_02 test - video sequence (source: BEA)

Propagation_03 test:

The propagation_03 test was carried out under the same conditions as the previous test.

After the oxygen supply hose was damaged (at 06:25 on the video[45]), the fire remained hidden inside the lateral compartment. Flames and a reddish glow were visible on several occasions at the rear of the structure (for example at 06:36 and 06:44), and appeared to vary in intensity thereafter. The flow of oxygen was audible throughout the test. Sparks were intermittently visible through the lateral compartment. Thick black smoke gradually invaded the test chamber.

At 06:57, the oxygen supply solenoid valve was closed. The sound of the leak disappeared and the intensity of the flames seemed to diminish instantly (the red glow radiated by the wall behind the lateral compartment diminished). The extinguisher was activated and thick, opaque smoke quickly filled the test chamber, making visibility almost nil. Visibility gradually returned after a few

[45] The timing indicated corresponds to that of the raw file of the Gopro camera recording.

minutes (at 10:50). No flames or red glow were visible; crackling noises were present and smoke escaped from the mask storage box. Flames reappeared in the vicinity of the mask storage box four minutes after the activation of the fire extinguisher.

Audio elements: the piercing of the mask hose 14 s after the fire was started was preceded by crackling noises (picked up by the microphone of the oxygen mask). When the hose was pierced, there was a broadband noise (leaking noise) followed 0.5 s later by a sound runaway. Cutting off the oxygen supply - which preceded the use of the extinguisher - interrupted the leaking noise.

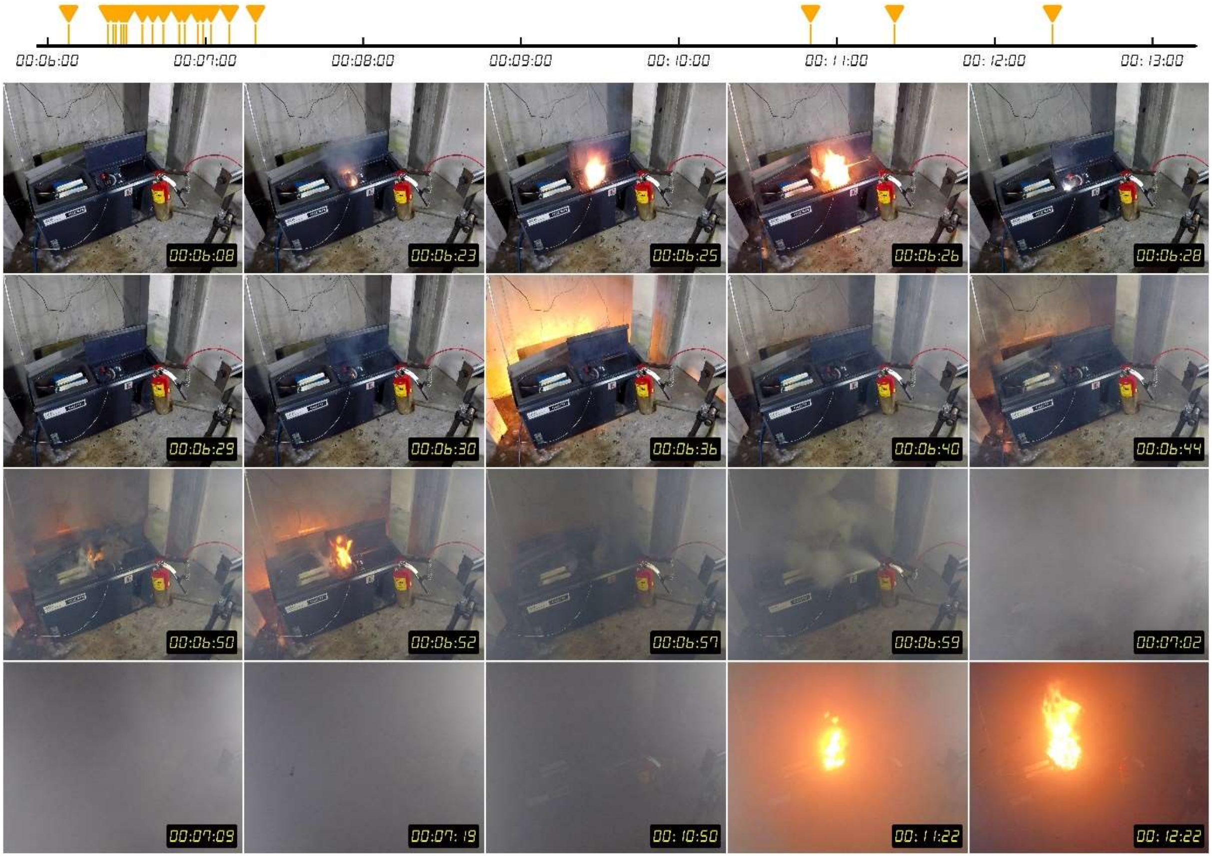


Figure 56: Propagation 03 test - video sequence (source: BEA)

During the test, the fire was concealed in the lateral compartment. The technique of fighting the fire with a halon fire extinguisher could not be applied. It is recommended to aim at the base of the flames, and if necessary, when the flames are inaccessible, to perforate the vertical wall of the compartment and slide the nozzle of the extinguisher into it before activating it. As the extinguisher was activated from the outside, it was not possible to accurately direct the extinguishing jet onto the flames, which may explain why the fire started up again after several minutes.

5.5 Summary of fire propagation with the addition of oxygen

The addition of oxygen to a flame (whatever its origin) makes the latter physically change. Introducing a lit cigarette into an oxygen-rich environment instantly ignites the glowing part and the cigarette burns completely in a few seconds.

The flow of oxygen-enriched gas directs the flame in the same way as a torch flame. In tests using a fire box, the flames were contained within the box and did not appear to emerge (the oxygen supply pipe sent a horizontal jet parallel to the bottom of the box). During large-scale tests carried out in mask storage boxes placed inside or outside lateral storage compartments, the flames were visible and emerged from the mask storage box in which the leak had been created.

In a fire fuelled by an oxygen leak, the colour of the flames is whiter because the combustion is richer in oxygen. This colouration reflects the high temperature of the fire. This characteristic variation in flame colour was observed in all the tests carried out as soon as an oxygen leak - controlled or uncontrolled - occurred. The flames were more intense and larger as soon as oxygen was added.

From a sound point of view, the oxygen leak was audible and the noise masked any other crackling noises heard when the fire was not supplied with oxygen. These crackling noises reappeared as soon as the oxygen leak was cut off.

The materials used in the cockpit comply with requirement CS25.853, which specifies that these materials must be self-extinguishing. However, in the case of an oxygen-fed fire, these materials are subjected to more demanding conditions than those of the certification tests.

In the tests, in the case of a "classic" fire, before the presence of an oxygen leak, the fire remained confined to the mask storage box where it started. It did not spread to the rest of the lateral compartment.

However, as soon as there was an oxygen leak, the fire spread rapidly:

- inside the lateral compartment, causing a concealed fire, which, with time, could emerge to spread to the rest of the lateral compartment;
- outside the lateral compartment, to the other oxygen mask storage box, to the document storage compartment that may contain flammable materials (documents etc.).

CONCLUSION

In the tests carried out in the presence of oxygen, fire spread rapidly from where it initially started, even to fire-resistant materials. Flames were whiter in colour, indicating a hotter fire. Thick black smoke was emitted from the fire. The sound of leaking oxygen was audible until the oxygen supply was cut off, and masked crackling noises. The sound of a fire fuelled by leaking oxygen was characteristic, comparable to that of a blowtorch.

5.6 Results of Oxygen fire study in connection with accident to the A320 registered SU-GCC

The audio analysis of the tests carried out as part of the Oxygen fire study gave the following results:

- the introduction of an external, glowing or ignited object into an oxygen mask storage box enriched with oxygen can cause slow combustion of the protective elements of the oxygen distribution hoses; the hose can be pierced between 13 and 28 s after the introduction of the exogenous element. The slow combustion prior to piercing is accompanied by characteristic crackling noises;

- when the entire mask caught fire, a sound runaway comparable to that produced by a blowtorch is present;
- a screeching noise may precede the loss of signal from the oxygen mask microphone;
- the degradation mechanism produced by the propagation of the fire to the storage box environment (lateral storage compartment) can show uncontrolled, random variations in terms of the level and timbre of the sound. During these tests, there was an interruption in the leaking noise for half a second followed by a detonation.

Comparison with the CVR recording of flight MS804 (see following figure):

- no crackling noise was present in the mask microphone recording;
- a sound runaway could be heard on the co-pilot mask microphone and CAM channels at 00:25:31 (EVT6);
- a screeching noise preceded the loss of the co-pilot mask microphone signal at 00:25:33 (EVT7);
- a momentary interruption (510 ms) in the oxygen leaking noise occurred at 00:25 :42 (EVT8).

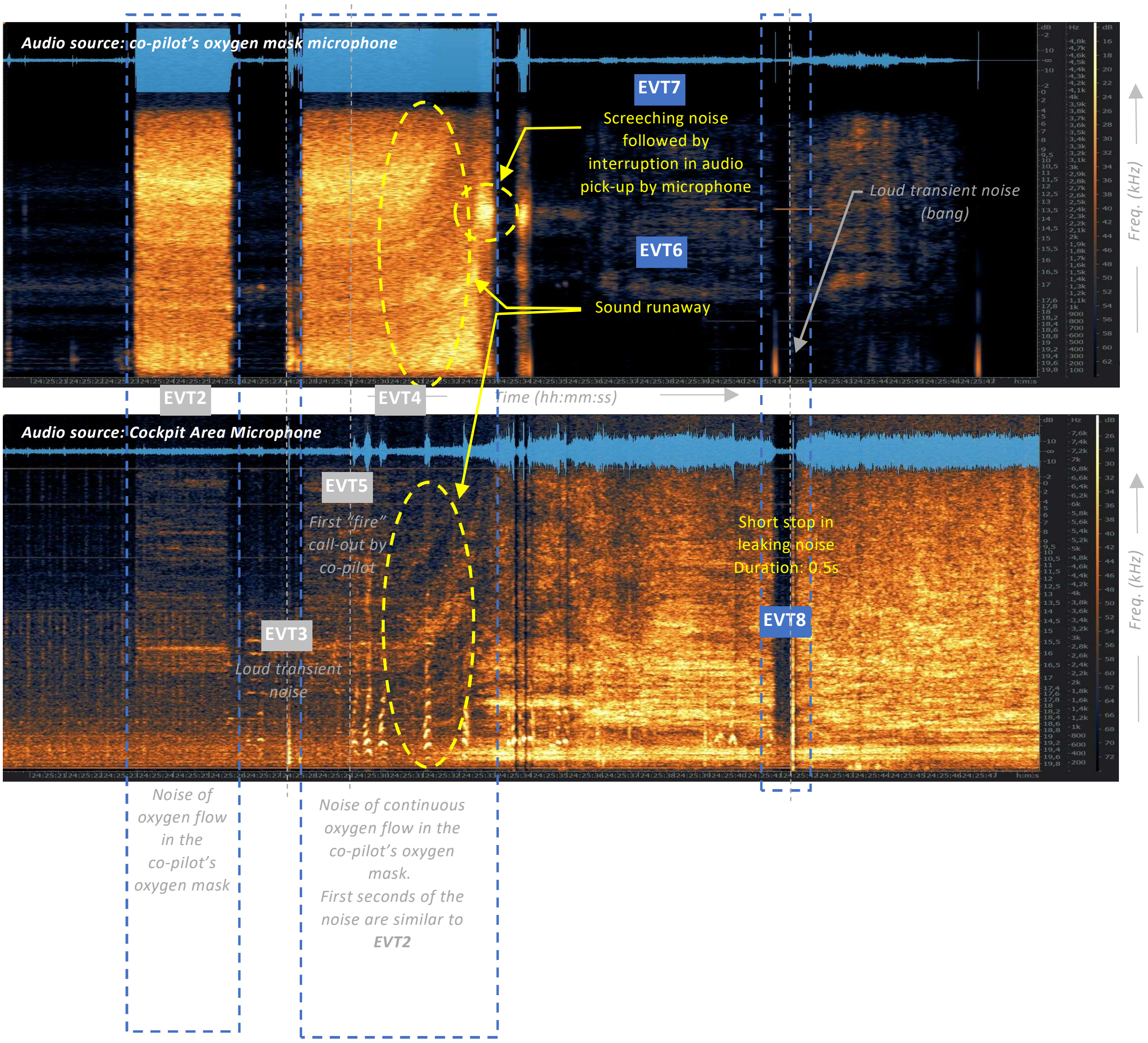


Figure 57: part of spectrum - waveform - flight MS804 (source: BEA)

5.6.1 EVT3: loud transient noise (t0 + 4.3 s)

None of the tests produced a sound similar to that corresponding to EVT3.

In the test conditions, the sound corresponding to the runaway of a lithium battery did not correspond to event 3; moreover, the dynamics of the event (presence of fire in the mask storage box immediately after the transient noise) does not support this hypothesis.

In the hypothesis of a “particle impact ignition” linked to the acceleration of a particle under the first flow of oxygen, there would be an interval of five seconds between the acceleration of the particle and the loud transient noise. The transient noise would not directly be the noise corresponding to the impact of the particle, but to a subsequent detonation or damage. The "particle impact ignition" and therefore its consequences were not reproduced.

A spark was used to create a controlled ignition in the device; this did not generate a detonating effect and the rupture of the hose that followed a few seconds later did not produce a loud transient noise.

In none of the next three candidate events was it possible to measure a noise with the same acoustic properties as the transient noise corresponding to EVT3:

- lithium battery runaway;
- rupture of an oxygen hose of the storage box and oxygen mask assembly;
- damage following particle impact.

Findings-Intermediate conclusion
The loud transient noise picked up by the oxygen mask microphone (at t0 + 4.3 s) probably does not correspond to the sound of a lithium battery runaway, nor to that of the rupture of a hose carrying oxygen pressurised to 5 bars.

5.6.2 EVT5: The co-pilot indicated the presence of a fire (t0 + 6.1 s)

The introduction of an external, glowing or ignited object into an oxygen mask storage box enriched with oxygen caused slow combustion of the protective elements of the oxygen distribution hoses of the assembly. The slow combustion was accompanied by characteristic crackling sounds that can only be perceived on the oxygen mask microphone signal. The hose was pierced between 13 and 28 s after introducing the external element (flame or cigarette).

No crackling noise was present in the co-pilot’s oxygen mask microphone recording.

Findings-Intermediate conclusion
The absence of crackling prior to the ignition does not support the hypothesis that a burning element was introduced into the oxygen box, i.e. an element outside the oxygen hose such as a glowing cigarette.

The various tests carried out to damage the oxygen assembly (either by dropping a cigarette or by placing a flame in direct contact with the elements contained in the mask storage box) showed that the hoses that carry the oxygen in the box had to be exposed for between 15 s to more than 50 s before there was irreversible damage and the flexible hose was pierced.

The suddenness of the phenomenon (EVT3__see paragraph 3.7.2) which preceded the start of the continuous leak (EVT4 and EVT9) and the rapidity of the sequence (sound events versus crew call-outs) seem to favour the hypothesis of the occurrence of internal damage to one or more of the components carrying the oxygen in the box (box, hoses, mask regulator, etc.) or to one or more of the sub-assemblies that make them up (connectors, filters, elbows, etc.).

Findings-Intermediate conclusion
The rapidity of the sequence (6 s between the first sound of the oxygen flow and the first fire call-out by the crew) supports the scenario of internal damage to the co-pilot's oxygen system, in which the appearance of an oxygen leak and the start of a fire fuelled by this leak would be almost simultaneous.

5.6.3 EVT6 and EVT7: modification of the continuous leaking noise: sound runaway and loss of signal from the co-pilot's oxygen mask microphone (t0 + 7.6 s and t0 + 9.6 s)

The sound runaway was reproduced during cigarette tests and fire propagation tests in the lateral storage compartment. During the cigarette tests, the use of a mask storage box with a glass panel made it possible to identify that the sound runaway corresponded to the ignition of the contents of the storage box (mask and hoses).

The screeching noise prior to the loss of the signal from the mask microphone was reproduced during a cigarette test.

Findings-Intermediate conclusion
The contents of the storage box for the co-pilot's oxygen mask caught fire at 00:25:31 i.e. att0 + 7.6 s (causing a sound runaway). The microphone on the co-pilot's oxygen mask was destroyed by the flames at 00:25:33 i.e. at t0 + 9.6 s.

5.6.4 EVT8: interruption in oxygen leaking noise (t0 + 17.9 s)

The fire tests in the lateral storage compartments showed that the degradation mechanism produced by the propagation of the fire to the environment of the mask storage box presented significant and uncontrolled variations in terms of the differences in the audio phenomena picked up with random variations in the level and timbre of the sound. During these tests, an unexplained interruption in the leaking noise followed by a detonation was reproduced.

Findings-Intermediate conclusion
The momentary interruption in the leaking noise may be linked to damage to the oxygen assembly located in or under the lateral storage compartment.

5.6.5 EXT EVT: activation of a fire extinguisher

The noise generated by the activation of a fire extinguisher (see appendix, Air Formation) was recorded and compared with the audio recording of the CVR of flight MS804. This comparison did not make it possible to isolate a noise lasting 12 to 17 s characteristic of the use of a fire extinguisher.

Findings-Intermediate conclusion
There is no audio evidence to confirm or not that a fire extinguisher was used in the cockpit.

6. CONCLUSIONS CONCERNING ACCIDENT TO AIRBUS A320, REGISTERED SU-GCC, OPERATED BY EGYPTAIR ON 19 MAY 2016

6.1 Findings

Only the facts relating to the oxygen leak and fire in the cockpit are set out below.

The co-pilot's oxygen mask microphone was active during the last 30 min of the CVR recording, and most likely from the start of the CVR recording.

The co-pilot's boom mike could not be used to transmit radio communications for the last thirty minutes, and most probably for the last two hours. The co-pilot, as PF on the flight, did not need to use his boom mike before reaching FL100 and used his hand-held microphone when needed during the cruise. Therefore, the co-pilot had no opportunity to detect that his boom mike was inoperative. This explains why the activation of the mask's microphone might not have been detected.

For the duration of the CVR recording, the co-pilot's oxygen mask microphone picked up low transient noises of elements being moved close to the document storage compartment. This pick-up could be heard on the co-pilot's loudspeaker (depending on the volume selected).

No evidence from the cockpit voice recordings confirms or refutes the hypothesis that people were smoking in the cockpit.

There was no mention of any intention or action on the part of either of the pilots to use the personal oxygen equipment.

The co-pilot's oxygen mask was not in the permanent *EMERGENCY* position before t0, start of the oxygen flow sound.
The dilution control on the co-pilot's oxygen mask was in the 100% position.
The storage box for the co-pilot's oxygen mask was not in the reset position.
A flow of oxygen via the co-pilot's mask lasting 2.6 s began at 00:25:30 (t0).
The flow is equivalent to that caused by pressing the *EMERGENCY* knob on the mask.

An event leading to a loud transient noise of unknown source occurred in the co-pilot's mask storage box 4.3 s after the start of the first flow of oxygen in the mask (t0 + 4.3 s).

The loud transient noise picked up by the oxygen mask microphone (at t0 + 4.3 s) probably does not correspond to the sound of a lithium battery runaway, nor to that of the rupture of a hose carrying oxygen pressurised to 5 bars.

There was a continuous uncontrolled leak lasting 3 min 23 s in the co-pilot's mask storage box corresponding to the complete emptying of the oxygen cylinder (start: t0 + 4.7s).

A fire was present in the cockpit at t0 + 6 s.

The contents of the storage box for the co-pilot's oxygen mask caught fire at 00:25:31 i.e. t0 + 7.6 s (causing a sound runaway)

The microphone on the co-pilot's oxygen mask was destroyed by the flames at 00:25:33 t0 + 9.6 s

The absence of a crackling sound prior to the ignition does not support the hypothesis that a burning element was introduced into the oxygen box (i.e. an element outside the oxygen hose).

The rapidity of the sequence (6 s between the first sound of the oxygen flow and the first fire call-out by the crew) supports the scenario of internal damage to the co-pilot's oxygen system, in which the appearance of an oxygen leak and the start of a fire fuelled by this leak would be almost simultaneous.

The interruption in the oxygen leaking noise (at t0 + 17.9 s) lasting 0.6 s was not linked to a crew action.

The momentary interruption in the leaking noise may be linked to damage to the oxygen assembly, located in or under the lateral storage compartment.

There is no audio evidence to confirm or not that a fire extinguisher was used in the cockpit.

When the "Lavatory Smoke" warning first sounded, i.e. 47 s after the start of the event at 00:26:17, the cockpit door was closed. It was then in the open position (at 00:26:48 and 00:27:18, potentially continuously over this period) before being closed again.

The cockpit door was likely closed when the autopilot was disengaged and the CVR stopped operating at 00:29:54, i.e. t0 + 4 min 24 s.

The data recorder did not record any change in parameters that could result from an action by the crew after the autopilot was disconnected.

6.2 Scenario

Context of flight

The Airbus A320 registered SU-GCC, took off from Paris-Charles de Gaulle bound for Cairo at 21:21. The event occurred when the aeroplane was cruising at FL370 with the autopilot engaged, after three flight hours. The co-pilot was the Pilot Flying (PF) and the captain, the Pilot Monitoring (PM).

Previously, there had been a lot of back and forth activity in the cockpit to deal with a sick passenger. After a moment's discussion between crew members, the captain had just announced that he wanted to rest and had asked for a blanket and pillow. Initially PM, he had probably passed communications to the co-pilot. Before that, the co-pilot had already made some communications with his hand mike. As usual above FL 100, neither of the pilots were wearing their headsets.

At this point, the two flight crew members and a cabin crew member were present in the cockpit. Music could be heard in the cockpit (the music was present throughout the recording by the cockpit area microphone).

Storage box for co-pilot’s mask not reset and mask microphone active

Noises of elements being moved close to the co-pilot's document storage compartment were also recorded on the CVR. They might have been heard on the co-pilot’s loudspeaker, as the co-pilot’s oxygen mask microphone was active.

The fact that the co-pilot’s oxygen mask microphone was active might have been due to:

- the storage box being in the non-reset position;
- a faulty component in the storage box.

First oxygen flow

The first event of the accident sequence that could be identified was a flow of oxygen for 2.6 s via the co-pilot’s mask regulator. This flow had the same characteristics as when the *EMERGENCY* knob of the mask is pressed when the box is not reset. The investigation was not able to determine if this flow was linked to a human action.

The noise of this oxygen flow could be heard in the cockpit. At this moment, the captain, possibly on hearing this noise, questioned the co-pilot.

The storage box of the co-pilot’s mask was thus highly enriched in oxygen as a result of this flow.

Start of leak

An event leading to a loud transient noise of unknown source occurred at this point in the mask storage box. It has not been possible to determine what generated this loud noise.

Less than half a second later, the noise of an oxygen flow, as when the *EMERGENCY* knob is pressed, appeared again. The noise evolved into a continuous leaking noise in the co-pilot's mask storage box.

Fire break-out and spread of fire

The co-pilot's call-outs indicated that a fire was present less than two seconds after the start of the continuous leak. The sound runaway indicates that the fire was present in the co-pilot's mask storage box. The fire spread to the exterior of the mask storage box.

The captain asked for a fire extinguisher to be brought to him. It has not been possible to determine whether the extinguisher was used. None of the pilots were wearing masks. As one of the two hoods and the halon fire extinguisher were on the co-pilot's side in the immediate vicinity of the fire, it is likely that these two items of equipment quickly became inaccessible to the crew.

Coughing sounds were heard. It was not possible to determine the level of breathability of the air or the level of visibility in the cockpit at the time. It is possible that the smoke made the air difficult to breathe and reduced visibility from that point onwards.

Smoke spread into the toilets and the avionics bay.

The cockpit door was opened and closed several times.

The leaking noise stopped for 0.5 s. This interruption was not due to any deliberate action to cut off the oxygen, but probably to the fire having damaged various components. The leak stopped after 3 min 23 s.

The fire continued to spread, shown by the crackling sounds on the audio recordings.

The cables powering several computers were damaged and several redundancies were lost. The on-board systems disconnected the autopilot.

No crew actions were recorded in the cockpit. It has not been possible to determine whether the crew remained in the cockpit, whether they were unconscious or whether they fled the fire and then returned or remained outside the cockpit.

The recorders stopped operating when the aeroplane was in cruise at FL370. The aircraft turned successively to the left and right in a descending turn and then collided with the sea.

6.3 Scenario based on presence of explosives

In December 2016, the EAAID announced the discovery of traces of explosives on human remains. This lead the BEA to study this hypothetical scenario.

The mapping of the accident site on the sea bottom found that all the extremities of the aeroplane were within the identified rectangle: the cockpit, the wings and the tail. These observations, together with the small size of the debris, lead to the conclusion that the aeroplane had collided with the surface of the water under high energy, and ruled out the scenario of the aeroplane having broken up in flight.

The BEA audio database contains some audio samples from on-ground and in-flight explosions produced by explosive material or missile strikes. The sound produced by the explosion picked up by the cockpit microphones was very different to the sounds recorded on the CVR of the event.

The BEA audio database contains audio samples from in-flight accidental depressurizations. These include loss of windshield in the cockpit, activation of explosive charge on a passenger, loss of cargo door and activation of an explosive in the cargo hold. The associated noises are different: total saturation of all the microphones for a long time or explosion followed by a blast or loud noise with a release noise or loud noise and the CVR stopping. All these sounds are very different to those on the CVR of the MS804. Sudden aircraft depressurization produces a very different sound to the one recorded on the CVR of the event where there was a long audio phenomenon (3 min) associated with a decrease in its level and timbre. Furthermore there was no depressurization warning.

No explanation related to the presence of an explosive could explain the first event of the accident sequence that could be identified, i.e. a flow of oxygen for 2.6 s via the co-pilot's mask regulator.

Regarding the event leading to a loud transient noise that occurred later, the comparison of the transient noise level on the four audio sources recorded by the CVR showed that the sound was louder (and longer) on the co-pilot CVR channel compared to the 3rd Crew and CAM channels. This leads to the conclusion that the transient noise originated inside the co-pilot's oxygen mask box or in the near vicinity of it and that this noise was not loud enough to be attributed to explosives.

In conclusion,

The possible discovery of traces of explosives on the aeroplane's occupants, even in several places, does not in itself make it possible to conclude that there was an explosion on board, when all the other physical evidence is incompatible with the scenario of an explosion that damaged the plane's structure or systems to the point of rendering it uncontrollable.

6.4 Safety issues

The certification requirements stipulate that the oxygen system shall be free from hazards in itself, in its method of operation, and in its effect upon other components. It is also stipulated that the impacts of an external source of ignition shall be minimised and that the immediate environment shall be preserved, i.e. an oxygen leak cannot cause the ignition of substances close by.

During flight MS804, the presence of emergency oxygen in the cockpit clearly contributed, if not to the outbreak, at least to the speed and the extent to which the fire spread in the cockpit.

This was also the case for several events on the ground. In all these events, which could be described as precursors, a fire fuelled by an oxygen leak occurred on the ground, the aeroplane was evacuated and only the fire-fighting services were able to bring the fire under control.

Based on the data available for the analysis of the accident to flight MS804 and the tests carried out as part of the Oxygen fire study, the following safety issues need to be considered:

- external heat sources in the vicinity of the oxygen which might have been the cause of the outbreak of a fire affecting the oxygen system components;
- the impact of contamination and internal ignition processes. The replacement of the storage box of the co-pilot's mask a few flights before flight MS804 led to the examination of the hypothesis of contamination of the mask supply hose during the maintenance operation;
- the failure of one of the system's components that might have caused a leak;
- the spread of a fire fed by an oxygen leak;
- the protection means available to the crew;
- the means to put out a fire fed by an oxygen leak.

6.4.1 External ignition sources to oxygen system

The data available for flight MS804 did not make it possible to determine the source of ignition of the fire in the co-pilot's mask storage box.

During the investigation, two potential ignition sources external to the oxygen system were mentioned: thermal runaway of a lithium battery and a lit cigarette.

6.4.1.1 Thermal runaway

As detailed in paragraph 5.2.1.1 Lithium battery tests, the document storage compartments located on the sides of the cockpit, near the oxygen masks, can be used to store electronic devices containing lithium batteries (smartphones, tablets or electronic cigarettes). There are specific procedures for fires involving the thermal runaway of lithium batteries. In the case of flight MS804, these detailed, in particular, the role of the PF and the PM, the use of protective equipment (mask and hood) and the fire extinguishing equipment (halon fire extinguisher if there are flames).

Following the event, a study carried out at Airbus revealed a potential fragility in the heat resistance of the glue used to assemble the panels of certain document storage compartments, raising concerns with respect to a fire propagation scenario initiated by the runaway of a lithium battery, followed by the collapse of the document storage compartments and the ignition of the oxygen distribution system. Following the identification of this risk, Airbus created a modification which consists in changing the material of the lateral stowage boxes from honeycomb to aluminium. This modification was subject to a monitored retrofit campaign.

In the scope of the Oxygen fire study, the BEA tested a number of electronic devices: the thermal runaway of their lithium battery(ies) was induced by the addition of heat; the sound and thermal effects were analysed.

The tests produced the following results. Firstly, the acoustic signature of the lithium battery runaways did not match the noise recorded on the CVR of flight MS804. Secondly, in the test conditions used in the study, the rise in temperature of the lithium batteries used in electronic tablets, electronic cigarettes and smartphones was not transferred to the surrounding environment and the incandescent particles did not ignite the materials. There was one outbreak of fire, linked to the presence of highly flammable material (adhesive tape) in the immediate vicinity of the battery.

In recent decades, lithium battery runaway has become a new risk to be taken into account, particularly in the cockpit, due to the use of electronic tablets.
The tests carried out did not reveal any particular fragility likely to correspond to an accident scenario for flight MS804 (based on the available data).
In other words, it is highly unlikely that a lithium battery runaway constitutes an element in the accident scenario for flight MS804.

6.4.1.2 Glowing cigarette

International regulations are not explicit about banning smoking in the cockpit of commercial air transport aeroplanes. While there are warnings about smoking near oxygen in the passenger compartments, there are no similar warnings with respect to the cockpit. The decision seems to rest with the captain.

In the case of flight MS804, the press reported information said to be taken from the judicial investigation suggesting that a member of the crew might have been smoking in the cockpit. No evidence from the cockpit voice recordings confirms or refutes the hypothesis that people were smoking in the cockpit.

With regard to the Boeing 737 accident that occurred on the ground before the accident to SU-GCC, the investigation showed that the captain had lit a cigarette two minutes before the fire broke out and the oxygen leak. The findings of the investigation highlighted a possible fragility created by smoking near a mask left in the *EMERGENCY* position.

During the tests carried out, handling a cigarette in the immediate vicinity of an oxygen-enriched mask storage box did not cause a fire to start. The same was true when hot ashes were introduced into the box. On the other hand, the introduction of a cigarette into an oxygen-enriched box accelerated its combustion, and if the cigarette was in contact with an oxygen supply hose, the fire could perforate the hose, causing pressurised oxygen to leak and create an oxygen-enriched fire that could rapidly spread.

No immediate, systematic and obvious danger has been established from smoking near an oxygen mask storage box, even with a mask in the EMERGENCY position or when the box has not been reset.

However, if a cigarette is introduced into the storage box – unlikely but possible - a fire may start, accompanied by an oxygen leak. In this case, the flames would be large and the fire would spread rapidly to the surroundings of the storage box.

6.4.2 Internal ignition sources

During flight MS804, the contents of the co-pilot's oxygen mask storage box caught fire. The absence of any prior crackling sound makes it unlikely that a burning object was introduced into the box. The rapidity of the sequence favours the scenario of internal damage to the co-pilot's oxygen system.

Tests have shown that in the event of an ignition inside the system, after an interval of a few seconds, the hose is ruptured, potentially resulting in a fire fuelled by the oxygen leak created by this same rupture.

The replacement of the storage box of the co-pilot's mask a few flights beforehand led to the examination of the hypothesis of contamination of the mask supply hose during the maintenance operation, which could have played a role in an internal ignition mechanism.

The particle impact ignition phenomenon described in literature i.e. the release of heat linked to the collision of a particle on a metal element, was not reproduced on the test bench used. However, given the limitations of the test conditions, this hypothesis cannot be ruled out.

The results of the electrostatic measurements carried out on the system make it highly unlikely that the ignition of system components or organic or synthetic debris in the storage box could be linked to electrostatic charges.

Moreover, the simple introduction of grease is not synonymous with an outbreak of fire. In other words, a fire will not systematically break out when grease and oxygen are brought together. However, this does not rule out the hypothesis.

In conclusion, although the hypothesis of internal damage to the system is favoured, the available data and the tests carried out have not made it possible to determine which internal ignition mechanism is likely to have occurred during flight MS804.

The tests carried out by the BEA were based on the assumption that the pressure in the system was 5 bar. Internal ignition mechanisms such as particle impact, grease oxidation or ignition by electrostatic discharge may depend on the oxygen pressure.

Additional tests could make it possible to:
- determine the conditions for spontaneous combustion of grease;
- determine the conditions for producing particle impact ignition and the resulting effects.

6.4.3 Propagation of oxygen-fed fire

The analysis of oxygen system hazards must look into the ability of a fire to propagate and burn through a component.

In the case of the fire on flight MS804, the analysis of the audio recording and those made during the tests showed the speed of the leak, along with the size of the fire and the speed at which it spread. The fact that no action by the crew was recorded subsequently also seems to testify to the extent and to the speed of the phenomenon.

This was also the case for events that occurred on the ground. In three of the events studied (see paragraph 3), the rupture of a hose under the action of the fire created an oxygen leak which fed the fire. These three events led to the evacuation of the cockpit.

In the presence of oxygen, the whiter flames are the sign of a hotter fire, and the materials are more inflammable. In an oxygen-enriched environment, a fire will spread rapidly despite the fire resistance of the materials in the immediate environment where it started.

6.4.4 Protective breathing equipment

When smoke or fire breaks out in the cockpit, one of the immediate actions is to protect the crew.

In the four accidents reviewed in this study, as the fire occurred on the ground, the crew members were able to evacuate the cockpit and the aeroplane.

In the case of the fire on flight MS804, the co-pilot could not use his oxygen mask and most likely could not remain in his seat. It is possible that the intensity and speed of the fire also made it impossible to use the hood (PBE) located on the right side of the cockpit.

In the case of SU-GCC, a second hood was available on the captain's side. However, this configuration is not systematic, and the possibility of a fire spreading in the environment of an oxygen mask on the same side as the hood seems not to have been considered when defining the fire procedures and determining the crew's means of protection.

6.4.5 Fire extinguishing equipment

At least one fire extinguisher must be present in the cockpit, and it must be suitable for fighting liquid fires and electrical equipment fires. Halon 1211 is one of the most frequently used agents. SU-CGC was equipped with halon fire extinguishers in the passenger cabin and cockpit.

During flight MS804, when the fire broke out, the captain asked for a fire extinguisher to be brought to him. As the cockpit fire extinguisher was in the immediate vicinity of where the fire broke out, it is not possible to know whether the captain was referring to this extinguisher or to an extinguisher in the cabin. From an acoustic point of view, it was not possible to isolate a sequence corresponding to the activation of a fire extinguisher.

In the four events that occurred on the ground, the fire required the intervention of the firefighting services. In two of the events, the crew members tried to extinguish the fire with the means at their disposal, but found that it was difficult to gain access to the cockpit (black smoke) and that the halon was ineffective.

During the tests carried out by the BEA (see paragraph 5.3 Extinguishing a fire in the presence of an oxygen leak: use of halon extinguishers), halon fire extinguishers were not effective in putting out a fire fuelled by a continuous oxygen leak. In order to stop the fire, halon combines with oxygen to reduce the latter's amplifying effect on the fire; however, a leak will constantly supply the fire with oxygen. In the test conditions, opaque smoke rapidly invaded the environment as soon as the fire extinguisher was used on an oxygen-enriched fire, considerably impairing visibility. In addition, the halon pyrolysis creates acid gases (HF, HCl, HBr) in harmful quantities for people nearby.

Halon fire extinguishers are therefore not suitable for treating fires fuelled by oxygen leaks. In many cockpits, however, these types of extinguishers are the only ones available.

In one of the tests carried out, the oxygen supply was deliberately cut off before the fire extinguisher was used. The idea was to act on the oxygen leak and therefore on the source of the fire's enrichment before attempting to extinguish it with a halon fire extinguisher. The sound of the leak disappeared instantly, the flames diminished and the spread of the fire slowed down.

6.5 Conclusion

The accident sequence began while the aeroplane was cruising at FL370, with a cabin crew member present in the cockpit, the captain resting in his seat and the co-pilot flying.

It has not been possible to precisely explain the start of the accident sequence. It is likely to have been an oxygen flow resulting either from pressing the *EMERGENCY* knob on the co-pilot's oxygen mask or from a component failure. A fire then started in the mask storage box, and was fuelled by a leak of pressurised oxygen. It has not been possible to determine which came first: the fire or the oxygen leak.

Whichever the case, the oxygen-fed fire spread to the outside of the storage box. This type of fire is rapid, large-scale and difficult to control. It produces a characteristic noise comparable to that of a blowtorch. The protective and extinguishing equipment items in the cockpit were not sufficient to bring the fire under control.

The fire damaged the computer power supply systems, which led to the disconnection of the autopilot in particular.

No crew actions were recorded in the cockpit. It has not been possible to determine whether the crew remained in the cockpit, whether they were unconscious or whether they fled the fire and then returned or remained outside the cockpit.

The aeroplane's flight path was uncontrolled and the aircraft collided with the sea.

7. SAFETY RECOMMENDATIONS

Note: in accordance with the provisions of Article 17.3 of Regulation No 996/2010 of the European Parliament and of the Council of 20 October 2010 on the investigation and prevention of accidents and incidents in civil aviation, a safety recommendation in no case creates a presumption of fault or liability in an accident, serious incident or incident. The recipients of safety recommendations shall report to the safety investigation authority which issued them, on the measures taken or being studied for their implementation, as provided for in Article 18 of the aforementioned regulation.

7.1 Further work taking into consideration the effects of overpressure in the oxygen system

The manufacturer of the oxygen equipment informed the BEA that there had been three recent occurrences of in-flight oxygen leaks. The tests as part of this Oxygen fire study had been completed when the BEA became aware of this.

These occurrences were classified as incidents and did not give rise to the opening of an investigation. The main elements of the three occurrences are as follows:

- Occurrence 1 In cruise at FL380 on an A321 on 29 March 2022

ECAM advice - crew oxygen 500 psi and dropping
The crew were alerted by the ECAM of a drop in oxygen pressure. The blinker on the captain's oxygen mask storage box indicated that there was an oxygen flow. The crew tried to reset the box. The oxygen flow suddenly increased and became noisy. The pilot took out the oxygen mask to try to solve the problem. A rapid and simultaneous flow occurred in all the other oxygen masks in the cockpit. The flow could not be stopped.

It seemed that at least one mask microphone was activated, but could not be reset. The crew's oxygen was switched off to stop the loud noise.

The rest of the flight was carried out at FL100, with two portable oxygen cylinders brought into the cockpit as a precaution.

A preliminary analysis indicated that an error in adjusting the oxygen bottle pressure regulator may have been the cause of the leak.

- Occurrence 2 In cruise on an A319 in January 2023

The crew noticed the sound of a leak and cut off the supply line. However, the leak continued until the cylinder was empty. After replacing the cylinder, the leak occurred again on the next flight.

- Occurrence 3 In descent from FL370 on an A319 on 28 May 2023

The captain's oxygen mask began to lose oxygen even though it had not been touched and was stowed in its box. The oxygen pressure in the cylinder dropped from 1300 psi to 150 psi in 5 s.

Following an initial analysis, it appears that a faulty installation or adjustment of the regulator installed on an oxygen cylinder supplying the cockpit could lead to overpressure in the entire system. In the event of overpressure (from 13 bar), the box status could change to “not reset”, the mask regulator could fail and a high-pressure leak could occur in one or all of the cockpit masks.

Further analysis is necessary to consider whether these events could lead to the examination of new hypotheses to try to explain the accident of flight MS804.

In particular,

An overpressure in the distribution systems is an additional hypothesis to consider in explaining why the mask microphone was active.

The first flow of oxygen present on the recording of flight MS804 is that of a flow via the mask regulator. An initial hypothesis was that the mask knob had been pressed, but overpressure in the system could be another explanation.

A few flights before the accident flight, the storage box of the co-pilot's oxygen mask had been replaced. A faulty regulator could be the common explanation for two unusual events: - the replacement of the storage box and the leak in the cockpit.

The overpressure is also a hypothesis to be considered to explain the short time in which the cylinder drained compared with the theoretical values.

The tests carried out by the BEA in the scope of this study were based on the assumption that the pressure in the system was 5 bar. Internal ignition mechanisms such as particle impact, grease oxidation or ignition by electrostatic discharge may depend on the oxygen pressure. Similarly, the fragility created by a nearby external source of ignition could be greater in the event of a high-pressure leak.

The general architecture of oxygen distribution systems - a high-pressure cylinder, a regulator, storage boxes, masks with regulators - can be found on most large commercial air transport aeroplanes.

Consequently, the BEA recommends that:

EASA, in collaboration with the manufacturers, carry out additional risk analyses to take into account the hypothesis of an overpressure in the distribution system and its consequences in terms of failure mechanisms. The results should be analyzed with regard to the potential factors explaining the scenario of flight MS804. These analyses may require additional testing as part of a research program.

[Recommendation FRAN 2023-024]

7.2 Propagation of a fire fed by an oxygen leak

The presence of the oxygen distribution system has a twofold impact: (1) The air may become enriched with oxygen in the vicinity of the supply system due to micro-leaks, mask tests or a rupture of a part in the oxygen supply system; the presence of oxygen makes the elements more inflammable and the start of a fire more likely. (2) A fire that damages the oxygen systems, if it causes a hose to rupture, becomes an oxygen-enriched fire that is difficult to control.

Certification requires that the occurrence of an uncontrolled oxygen fire is extremely unlikely. The accident to flight MS804 and previous similar events (on the ground) requires consideration to be given, not only to the means of preventing these fires, but to their propagation and the means of fighting them.

These events and the tests carried out have highlighted the size of the fire and the speed at which it spreads in the case of a fire fuelled by an oxygen leak. These fires produce a characteristic sound, comparable to that of a blowtorch, and significant heat (recognisable by the whiteness of the flame).

During flight MS804, when the fire broke out, the captain asked for a fire extinguisher to be brought to him. The aeroplane was equipped with a halon fire extinguisher in the cockpit. As this fire extinguisher was in the immediate vicinity of where the fire broke out, it is not possible to know whether the captain was referring to this extinguisher or to an extinguisher in the cabin. From an acoustic point of view, it was not possible to isolate with any certainty, a sequence corresponding to the activation of a fire extinguisher.

In the four events that occurred on the ground, the fire required the intervention of the firefighting services. In two of the events, the crew members tried to extinguish the fire with the means at their disposal, but found that it was difficult to gain access to the cockpit (black smoke) and that the halon was ineffective.

During the tests, halon fire extinguishers were not effective in putting out a fire fuelled by a continuous oxygen leak. In order to stop the fire, halon combines with oxygen to reduce the latter's amplifying effect on the fire; however, a leak will constantly supply the fire with oxygen. In the test conditions, opaque smoke rapidly invaded the environment as soon as the fire extinguisher was used on an oxygen-enriched fire, considerably impairing visibility. In addition, the halon pyrolysis created acid gases (HF, HCl, HBr) in harmful quantities.

Halon fire extinguishers are therefore not suitable for treating fires fuelled by oxygen leaks. In many cockpits, however, these types of extinguishers are the only ones available.

The existing fire-fighting procedures have not been designed to deal with the specific case of an oxygen fire. The tests carried out by the BEA show that these procedures are ineffective and even counter-productive in the case of an oxygen fire.

In events on the ground, the crews were unable to control the fires and evacuated the cockpit. In flight, fighting an oxygen-enriched fire requires the oxygen supply to be immediately cut off.

Consequently, the BEA recommends that:

- *whereas the occurrence of ground events and one in-flight event in which there was an uncontrolled oxygen fire;*
- *whereas a fire fuelled by an oxygen leak spreads rapidly and is large in size;*
- *whereas such a fire presents identifiable characteristics such as a noise comparable to that of a blowtorch and the colour of the flames;*
- *whereas fighting a fire of this type requires first and foremost the cutting off of the supply of oxygen;*
- *whereas the oxygen mask is one of the protective breathing devices;*

❍ ***EASA assess the appropriateness of cockpit fire/smoke procedures incorporating the recognition of an oxygen fire (identifiable by a characteristic noise comparable to that of a blowtorch) and the need for the immediate cutting off of the oxygen supply in this case, and if applicable, review the requirements for installing and carrying protective equipment independent of the oxygen distribution system.***
[Recommendation FRAN 2023-025]

7.3 Risks linked to the use of cigarettes in the cockpit

International regulations are not explicit about banning smoking in the cockpit of commercial air transport aeroplanes. While there are warnings about smoking near oxygen in the passenger compartment, there are no similar warnings with respect to the cockpit. The decision seems to rest with the captain.

In the case of flight MS804, the press reported information said to be taken from the French judicial investigation suggesting that a member of the crew might have been smoking in the cockpit. No evidence from the cockpit voice recordings confirms or refutes the hypothesis that people were smoking in the cockpit. The results of the tests carried out do not suggest that a lit cigarette contributed to the accident sequence.

With regard to the event that occurred on the ground four years previously on a Boeing 737, the investigation showed that the captain had lit a cigarette two minutes before the start of the fire and the oxygen leak. The investigation highlighted a possible fragility created by smoking near a mask left in the *EMERGENCY* position.

During the tests carried out in the scope of this study, it was found that handling a cigarette in the immediate vicinity of a mask storage box did not cause a fire to start even if this box was rich in oxygen. The same was true when hot ashes were introduced into the box. On the other hand, the introduction of a cigarette into an oxygen-enriched box accelerated its combustion, and if the cigarette was in contact with an oxygen supply hose, the fire could perforate the hose, causing pressurised oxygen to leak and create an oxygen-enriched fire that could rapidly spread.

No systematic and obvious danger has been established from smoking near an oxygen mask storage box, even with a mask in the EMERGENCY position or when the box has not been reset. However, if a cigarette is introduced into the storage box - unlikely but possible - a fire may start, accompanied by an oxygen leak. In this case, the flames would be large and the fire would spread rapidly to the surroundings of the storage box.

Consequently, the BEA recommends that:

- ***EASA ensure that:***
    - ***the danger represented by a glowing cigarette in the cockpit be taken into account and the associated risks assessed;***
    - ***certification and operational regulations be amended where applicable.***

[Recommendation FRAN 2023-026]

APPENDICES

Functional description of CVR audio system
Audio pick-up by oxygen mask microphone
Waveforms from CVR recording
EVT1
EVT2
EVT4 and 9
EVT8
Lavatory
Air Formation
Halon gas
Comparative audio analysis for EVTS 6 7 8
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Videos 1,2,3&4